Understanding Chemical Bonding

The development of A level students' understanding of the concept of chemical bonding

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abstract

A level chemistry students' developing understanding of the chemical bonding concept was investigated using a grounded theory approach. Sequences of in-depth interviews with individual students were supplemented by a range of complementary data sources. The thesis presents case studies of two of the students, as well as describing general features that emerged during the research.

It was found that several aspects of the orbital concept were not well understood by the students. Students were found to have alternative conceptions of how electrostatic charges interact, and they often failed to appreciate the role of such electrostatic interactions in the formation and breaking of chemical bonds. It was also found that there was widespread use of inappropriate explanatory schemes based upon the notion of a 'full [electron] shell' or 'octet' as the rationale for the occurrence of chemical bonds and chemical reactions. Progression in understanding chemical bonding amongst these A level students largely concerned the transition between this alternative 'octet thinking' and the electrostatic explanatory schemes of curriculum science. This finding is used to provide advice to teachers, text-book authors and science curriculum planners.

This thesis contributes to a number of contemporary debates concerning the nature of learners' alternative ideas in science. It is demonstrated that individual learners do hold coherent and stable explanatory schemes that are inconsistent with curriculum science. Moreover, learners hold multiple frameworks in cognitive structure to explain the same phenomena. It is also shown how, in learning chemistry, alternative conceptions deriving from intuitive theories about the physical world may be less significant than those based on material that is taught incorrectly, or that is presented to learners who do not have the prerequisite knowledge to construct the intended meaning.

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Chapter 1.

Introduction to the thesis: the importance of the study.

> "At the most general level there are a few concepts that are very integral to the way in which chemists approach the natural world. Concepts like *bonding, structure, rate of reaction,* and *internal energy* apply to all chemical systems. These are ... powerful ideas that provide structure for whole areas of knowledge. Once such a concept is grasped it provides a framework in which the learner can confidently face new learning ... As the learning itself proceeds the understanding of the concept itself grows ever richer."
> (Fensham, 1975, pp.199-200, italics in original.)

§1.0: The character of the research.

This thesis discusses aspects of how understanding of the concept 'chemical bond' develops. The research was undertaken with students following a General Certificate of Education Advanced Level (henceforth 'A level') Chemistry course in a Further Education College in England. These learners would have been introduced to some basic ideas about chemical bonding during their school courses, at the General Certificate of Secondary Education level (G.C.S.E. - now known as Key Stage 4 (KS4) in the English school system). Learners' ideas about chemical bonding were elicited near the start of their A level course, and then their progression was investigated.

The thesis is based on a small scale study primarily using in-depth interviews with individual learners taking A level chemistry at a single centre. (A schedule for the interviews is provided in appendix 1, along with a digest of the other data analysed for the research.) In this sense the research is somewhat provisional in nature. However, the research has followed the principles of 'grounded theory' (discussed in chapter 4), in that data has been collected and analysed to build a model (presented in chapter 6, and discussed in chapter 12) which is suitable for formal testing. Although some provisional survey work has been carried out to demonstrate the feasibility of testing the general applicability of the model (described in appendices 2 and 3), the present thesis is primarily concerned with the *development of the model* as an authentic interpretation of the data collected, rather than with its testing.

In this introductory chapter I will explain the importance of the focal concept of chemical bonding, and why developing understanding of this concept is an important research topic in science education.

§1.1: The importance of the chemical bond concept.

Chemical Bonding is a key idea in chemistry which is used at all educational levels, and which is needed for an understanding of much of the subject. Fensham has called it one of the "big concepts in chemistry" and (in the quotation used as a motto above) described it as one of the "powerful ideas that provide structure for whole areas of knowledge" (Fensham, 1975, pp.199-200).

Chemistry may be defined as the science that characterises material substances, in particular through their interactions (for example the Longman Modern English Dictionary defines chemistry as "the study of the composition, properties and structure of substances, and of the changes they undergo", Watson, 1968, p.188). Although such chemical reactions could be - and historically have been - studied descriptively, chemistry as a science seeks to explain observed patterns in terms of a theoretical framework. Central to this framework is the notion that all substances are comprised of arrangements of elemental particles *bound* together, and that reactions involve rearrangements of these particles. Thus chemical reactions involve the breaking and making of chemical bonds, and explanations of chemical reactivity relate to the reasons for, and mechanisms of, bond breaking and bond forming.

The particles often described as elemental in chemistry are atoms (although it will be argued in chapter 12 that this may not be the most appropriate conceptualisation). In terms of the theoretical framework, chemistry may be considered to be largely about the rearrangements of groups of atoms, and therefore about the making and breaking of bonds between atoms. Indeed, chemistry *has* been described as "the making and breaking of chemical bonds" (Linnett, quoted in Pickering, 1977, p.1), and it has been claimed that understanding the chemical bond is *central* not only to chemistry, but "to all fields of molecular science" (Zewail, 1992, p.xi).

The centrality of this topic to chemistry is recognised by the Associated Examining Board which sets the syllabus for the A level Chemistry examination that is sat in the College where the research was undertaken (Associated Examining Board, 1996). Indeed at the time of writing the A level Chemistry syllabus content is "arranged into four major themes" the first of which is "Structure and Bonding" (the others being "Physical Chemistry", "Inorganic Chemistry" and "Organic Chemistry").

Textbooks intended to support A level chemistry courses usually have one or more chapters on bonding as part of the early material which provides the theoretical foundation for the subject (e.g. Ch.5 of Andrew and Rispoli, 1991; Ch.2 of Atkins et al., 1988; Ch.2 of Freemantle, 1987; §1.5-§1.6 of Fullick and Fullick, 1994; Ch.8 - Ch.10 of Hill and Holman, 1989; Ch.3 of Lister and Renshaw, 1991; Ch.4 - Ch.6 of Maple, 1996; Ch.4 of Ramsden, 1994).

§1.2: The importance of studying learners' ideas in science.

In the past two decades there has been a great deal of research in science education looking at various aspects of student learning and learning difficulties. This was a response to studies which had drawn attention to difficulty that secondary schools pupils had understanding the conceptual base of physics and chemistry (Driver and Easley, 1978, p.79). This has been particularly so in the tradition of work described as the 'alternative conceptions movement', or 'constructivism', which is reviewed in chapter 2. The assumption has been that the more that is understood about learners' ideas about a topic, the more effective curriculum planning and teaching may be (e.g. Driver, 1983, p.76, c.f. §2.3.9, §2.3.10).

The centrality of chemical bonding to the study of chemistry makes it a fundamental concept area, and science teachers looking to educational research to inform and illuminate their teaching, might expect to find many informative studies discussed in the literature. In fact, this is not the case (Carmichael et al. 1990, Duit, 1991).

§1.3: The relative paucity of studies into student understanding of bonding.

There has been a great deal of research into learners' ideas about scientific topics (for example see the bibliography by Carmichael et al. 1990, and annual updates), much of it undertaken within the 'alternative frameworks' or 'constructivism' perspective (to be discussed in Chapter 2). However some areas of science have attracted more attention than others.

For example Duit (analysing another bibliography) reports 132 studies classified within the whole of chemistry, compared to 146 in Electricity and 281 in Mechanics - the two most 'popular' areas for research within physics (1991, Table 4.1, p.71). The chemistry-related studies covered areas of combustion, oxidation, chemical reactions, transformation of substances, chemical equilibrium, symbols, formula, mole concept - but not bonding. The bibliography referred to above, produced by Carmichael et al., (1990) contains only six references to studies of learning about bonding and structure. (Griffiths reports how he only found three papers that related to bonding, and, even then, "one of them ... incorporated all of the information contained in the other two", 1994, p.77).

So despite the accepted importance of chemical bonding as a concept, and the considerable activityof educational researchers investigating the understanding of various aspects of science, little attention has been paid to the topic of learners' understandings of chemical bonding. Although it is not possible to know exactly why this should be, it is possible to suggests three plausible factors:

- the nature of chemical knowledge (§1.3.1)
- the absence of preconceptions (§1.3.2)
- prerequisite knowledge (§1.3.3)

It will be argued that these factors

(1) make this a more complex area to investigate than others that have received much more attention from researchers (such as mechanics), and

(2) put such a study outside the 'main stream' of constructivist studies in science education.

However, in the present research these same factors were considered to provide extra interest to the work, as it is my intention that through this thesis I should contribute to the wider debates about (a) appropriate models of learning and progression in chemistry; and (b) suitable methodology for studies into student learning of science.

§1.3.1: The nature of chemical knowledge.

Chemistry, although an empirical science, has an extensive and rich theoretical structure. The same could be said of physics - where student understanding has been probed in much more detail - but it is my contention that the structure of theoretical knowledge in these two sciences is significantly different (c.f. §1.7 below).

Both subjects may be understood to involve building models. In physics these models are largely mathematical and to a large degree consistent across the subject (Gregory, 1988, p.vi, p.18. It should be noted that I am referring here to the formal public version of science as represented by the research literature, and not the personal knowledge of individual scientists which may well be less consistent: c.f. §1.7, below). Indeed where discontinuities do appear in the theoretical structure they receive much attention. (Perhaps the major examples are the shift from Newtonian mechanics to the alternative framework based upon Einstein's paradigm, and the apparent incompatibility of quantum mechanics with traditional branches of physics.) The basic concepts of physics include energy, force and momentum - concepts for which there are consensus meanings among physicists. Although it is *possible* to reduce the discussion of much of chemistry to applications of physics, this is not the way most chemists see the subject (e.g. Scerri, 1993.)

The perceived key concepts of chemistry are often those that are derived within the complex theoretical structure of the discipline - rehybridization, the inductive effect, polarisability, acids, oxidation, nucleophiles, resonance. Although it would be possible *in principle* to ultimately redefine such concepts in terms of a conceptual hierarchy based on a few fundamental concepts, this has not been how chemists perceive the subject. Whereas in physics practitioners are often content to conceptualise their subject in terms of a small number of fundamental ideas (charge, energy, etc.) in chemistry the subject is often developed by 'bootstrapping' one high level concept on another - a process that may readily become circular. (However this need not be a problem if, as Kuhn {1977, pp.xviii-xix} suggests, the meaning of concepts in science is not actually learnt through formal definitions, but by working through examples). In the case of concepts such as *chemical bond*, *acid* or *oxidising agent* there is no single definition as with momentum (i.e. p = m.v), but a series of meanings of different sophistication which are applicable in different specific contexts. Appendix 4 sets out an analysis of the concept of chemical bond as it might be discussed at KS4 (G.C.S.E.) level, and the additional discussion that might be introduced at A level. The abstract and multifaceted nature of the concept area being studied may readily grasped from this analysis.

The researcher who investigates student understanding of the force concept will be aware that the concept may be understood to different degrees, but should have a clear idea of what *the* physics meaning of force is. The researcher exploring student understanding of some chemical concepts has no single 'benchmark' for comparison.

As Paradowski has commented,

> "In physics it is possible to develop a simple and detailed model to explain certain classes of phenomena, but chemistry is too complex to be fully explained by such simple theories ... one needs several good models. But these 'good' models are more flagrantly models, i.e. they explain only a selection of data, and hence the need for several models."
> (Paradowski, 1972, quoted in Brock 1992, p.505.)

In my view this makes the work more interesting and rewarding, but this could well be one reason why understandings of chemical concepts have been explored less than those in physics, and why a key idea such as *the chemical bond* has received sparse attention. This issue will be discussed further, below (§1.7).

§1.3.2: The absence of preconceptions.

Much of the research into the understanding of scientific concepts has taken place from perspectives that has been collectively termed the 'alternative conceptions movement' (see chapter 2) which itself had roots in Piagetian studies into children's unschooled ideas about the world (§2.2.1).

Children have direct experiences they will associate with - for example - gravity and electricity, plants and the sun. They will form ideas about such phenomena. Children's experiences of chemical bonds are very indirect - and indeed it is unlikely that someone would come to hold a conception of chemical bonds in the absence of explicit *teaching* about atoms and molecules. Certainly learners would be expected to be familiar with the term 'bond' (as in glues, or family ties), and to bring their 'life-world' meaning of the word to classes. However, without some notion of the structure of matter at a molecular level, preconceptions about chemical bonds are unlikely to develop. Carr has pointed out that although learners' understanding of some science concepts is hindered by their everyday meanings for the word and their intuitive explanations of the phenomena,

> "Confusions and difficulties over a number of chemical concepts may require a different perspective, since these are abstract and formal explanations of invisible interactions between particles at a molecular level and are not likely to be arrived at from confrontation with the world of experience."
> (Carr, 1984, p.97.)

A similar point is made by Garnett et al., who have reviewed the literature on students' alternative conceptions in chemistry, and come to the view that some of the alternative ideas reported may well derive in part from the way topics are taught,

> "while there are many possible origins for these alternative conceptions as students construct new meanings based on the 'informal' or 'commonsense' knowledge they bring to instruction, our view is that some of these conceptions result from pedagogic practices, and, with carefully constructed instruction, their incidence could be reduced."
> (Garnett et al., 1995, p.72.)

(This possibility will be acknowledged below in the notion of an EPISTEMOLOGICAL LEARNING IMPEDIMENT, §1.5.5.)

Researchers interested in cataloguing quaint but false ideas about nature are more likely to investigate areas where young people form *spontaneous* conceptions, or 'intuitive theories', about natural phenomena. This is a second plausible reason why so little work has been carried out on understanding of bonding.

§1.3.3: Prerequisite knowledge.

Closely related to the last point is the extent of the prerequisite knowledge required for learning about chemical bonds. The importance of analysing a topic area to ensure that the required prerequisite learning is in place before the topic is taught is well established in chemistry (e.g. Gilbert, 1977, p.11; Kempa, 1977, pp.3-6).

Before students can effectively study bonding they must have some ideas about pure chemical substances compared to mixtures, and about the atomic theory, or 'particle theory'. These are topics which have received research attention, and where learning difficulties have been uncovered (see chapter 3, §3.1.1 and §3.1.2).

Further, in order to develop a suitable understanding of bonding concepts at A level, the learner needs to already understand basic electrostatic ideas involving the fundamental physics ideas of force and energy (see appendix 4 and 5). Again these are areas that have received considerable research attention, and have been found to be difficult for learners (§3.1.3).

The investigator hoping to enquire into the understanding of chemical bonding needs to take into account research findings from these prerequisite topic areas, which may help explain why bonding was not one of the topics that was considered an early priority in this type of research. It may also be the case that researchers with a physics background would be more likely to look at physics topics, whilst many chemical education researchers might have reservations about investigating a topic so closely *tied to* physics concepts. (I teach both Physics and Chemistry to A level, perhaps partly explaining my interest in this topic.)

§1.4: Assumptions about learning.

In order to proceed with an enquiry into learning of chemistry it is necessary to make some axiomatic assumptions about the learning process. Two central ideas I will use are that of *cognitive structure*, and *learning impediments*.

§1.4.1: Cognitive structure.

Ausubel and Robinson define cognitive structure as "the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to him at any point in time" (1969, p.51), although it might be suggested that this is actually a description of *the contents of* cognitive structure. When cognitive structure has been considered ***the knowledge someone possesses and the manner in which it is arranged*** it has been considered "ill-defined" (White, 1985, p.51), but the inclusion of reference to the ***arrangement*** of knowledge usefully augments Ausubel and Robinson's version. White's point was that we have very little knowledge about the appropriate 'units' or 'elements' in which to discuss 'knowledge' as held in cognitive structure, nor what exactly we mean by its arrangement. We may have much knowledge about memory function from psychology, and some detailed information about brain physiology - but we have a very limited understanding of how our notions relate to our neurons. For the purposes of this present thesis the following composite definition will be used:

cognitive structure:

the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to her at any point in time, and the manner in which it is arranged.

For present purposes then I will make the following assumptions, that I believe will be considered reasonable:

(1) that concepts are in some way 'stored' or represented in a learner's brain,

(2) and that there is some form of organisation of these representations (i.e. we accept the existence of cognitive structure);

(3) that therefore the notion of two concepts being more or less closely linked, connected or integrated in cognitive structure is a meaningful and sensible one;

(4) that we do not have direct access to a learner's cognitive structure;

(5) that a learner's behaviour (statements, responses to questions *etc.*) may be considered to reflect aspects of his or her cognitive structure;

(6) that we may *construct models* to *represent* cognitive structure in terms such as the various conceptions that a learner holds, and how they appear to be inter-related;

(7) that the utility of such models may be judged in terms of the extent to which they are consistent with, and may be used to organise and explain, the learner's behaviour (statements, responses to questions *etc.*)

§1.5: Learning impediments.

From a teacher's viewpoint intended learning may fail to occur for a range of reasons, including a student not being able to hear the teacher, or not being able to read the board, or not listening to instruction. Although issues of classroom organisation, student motivation, and so forth are important in managing effective learning, they are outside the scope of this present study.

My context is students who are present in class, and motivated to learn, and able to see and hear the teacher's presentation. When intended learning does not occur in such a context the research agenda may concern such issues as effective communication, shared meanings and misunderstandings. In this context I am going to refer to there being 'learning impediments', although this term is not used in the same sense of the learner having special education needs, or some deep psychological 'learning block' that interferes with learning in general (Bruner, 1979 {1962}, p.12). Rather these impediments will be conceptualised in terms of the intended learner's cognitive structure, and its relation to the material presented, but this does not imply that there is any sense in which the failure to learn is assumed to be the 'fault' of the learner.

I am using the term 'learning impediment' to mean *some aspect of existing cognitive structure which interferes with the effective learning of material during science teaching.* The term 'impediment' is thus used is a similar sense to 'barrier', i.e. as an obstruction, as something that acts as a 'mental block' to effective learning.

§1.5.1: A possible typology of learning impedimenta.

I am going to suggest that - for my present purposes at least - such learning impedimenta may be divided into categories according to their pedagogic implications. The first distinction I wish to draw is between what I will call *null* learning impediments, and *substantive* learning impediments.

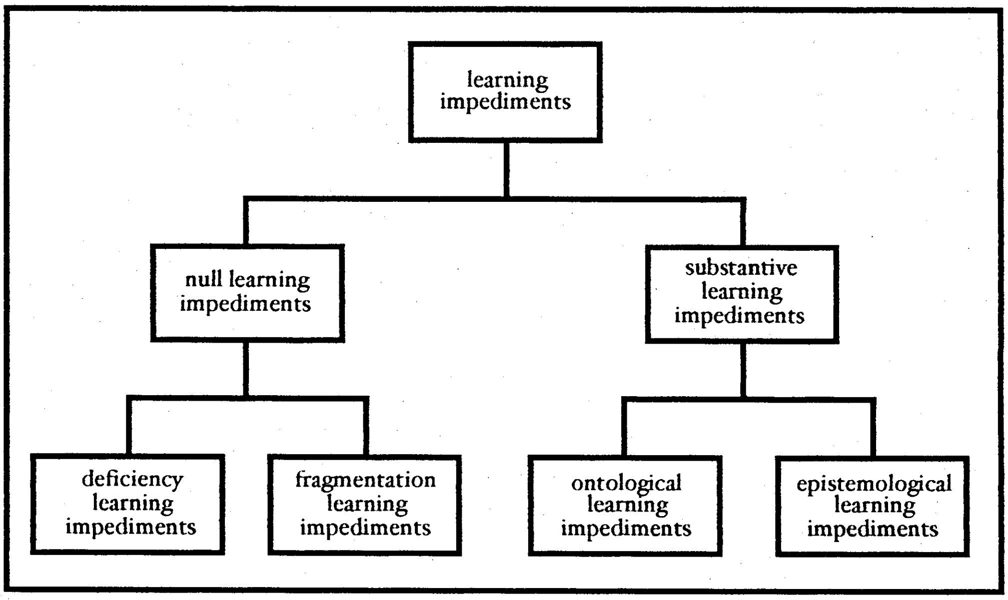
§1.5.2: Null learning impediments.

A NULL LEARNING IMPEDIMENT describes the situation where meaningful learning (§2.2.5) does not take place because the learner *does not make a connection* between the presented material and existing knowledge.

It may be that relevant material is held in cognitive structure, but that the learner does not *appreciate* its relevance, so the new material is stored as an unrelated fragment of knowledge. I will describe this case as a FRAGMENTATION LEARNING IMPEDIMENT. If this is diagnosed the teacher may act in this situation to make connections explicit.

Alternatively there may be a *deficiency* in cognitive structure, in that appropriate 'prerequisite learning' may not have taken place - that is the 'jump' between the existing structure and the 'target' structure is too large for the new material to be assimilated in one 'step'. For example a student on an advanced course may not have covered the expected material in her elementary classes for some reason. I will refer to this as a DEFICIENCY LEARNING IMPEDIMENT. In this situation remedial teaching is required.

A slightly different response is required where the material to be learnt is so highly abstract that there is no suitable prerequisite knowledge in the usual sense. Here the 'gap' must be 'bridged' through providing new experience on which to base learning, or through the use of analogies with familiar and more concrete situations (c.f. §2.3.10).



a typology of learning impedimenta

§1.5.3: Substantive learning impediments.

As opposed to NULL LEARNING IMPEDIMENTS, SUBSTANTIVE LEARNING IMPEDIMENTS are not caused by the absence of material perceived as relevant in existing cognitive structure, but in a sense are *due to its presence*.

In this situation the learner already has knowledge that *is recognised* as related to the new material being presented. However, the intended learning does not take place because the new material is seen to be inconsistent with the existing knowledge, or is seen to be related to existing cognitive structure in some inappropriate way. There are several possible outcomes here (c.f. §2.3.4):

i) perhaps no learning takes place, i.e. there is no substantial consequent change in cognitive structure. (It is unlikely that any experience would leave someone *completely* unchanged, and it might be expected that any exposure to teaching would lead to some shift in cognitive structure. However we will assume that in some cases the changes may be considered as trivial, in the sense of being very small changes, or peripheral, in the sense of not involving changes close to the 'target', and therefore negligible.)

ii) alternatively the new material is used to develop the existing conceptual framework, but in order to maintain consistency the meaning of the presented information is changed as it is reinterpreted by the learner;

iii) learning takes place, but in order to avoid contradiction, the new material is not associated with the intended framework of ideas, but is connected elsewhere in cognitive structure. (Ultimately all knowledge that is held in cognitive structure is connected, but I will assume that such connection may be so indirect in some cases that for most purposes the knowledge fragments are not perceived as related.) This will lead to fragmented learning.

In order to avoid such outcomes the teacher needs to help the learner 'debug' the existing cognitive structure, and this process has received a lot of attention in the constructivist science education literature. This requires both the diagnosis of alternative conceptions and strategies for bringing about conceptual change (see chapter 2, especially §2.10).

It is suggested here that to a first approximation SUBSTANTIVE LEARNING IMPEDIMENTS may be considered as *ontological* or *epistemological* - although this distinction perhaps has less to do with their *ultimate* status than how the teaching profession should best avoid them.

§1.5.4: Ontological learning impediments.

There has been much research into children's intuitive ideas about how the world is (see chapter 2). For example Ogborn has been involved with research which examines the categories which learners tend to use to think about the world, (Mariani and Ogborn, 1991) and with Bliss has described what they call a common-sense theory of motion (Bliss and Ogborn, 1993).

The term *intuitive* may seem to suggest that we are in some sense concerned with *a priori* knowledge, such as Kantian categories that are reached by pure thought alone (e.g. Russell, 1961). It does seems likely that some aspects of the structure of the human brain predispose us to think along certain lines. In former times many would have put this down to an act of special creation: that is, our minds reflect our creator and resonate with the rest of His creation. A more contemporary explanation might suggest that brain evolution has been constrained by physical law, and has been contingent on our environment. For example there has been research into the so-called natural kind categories that are believed to be recognised across cultures (e.g. Gelman and Markman, 1986). If there is survival advantage in having a brain that predisposes one to recognise such categories as fish (found in water, usually edible), trees (useful for hiding, often have edible parts) or large, sharp toothed carnivores (caution recommended) it is understandable such brain structure has evolved. (For such purposes the subtleties of scientific taxonomy may have less utility value, so that in general spiders may be categorised with 'insects', but not classed as 'animals'.)

Whatever predispositions there may be, actual concept development requires experience of the world. So our beliefs about *the way the world is* are a product of our experiences as processed through brains which have evolved according to physical laws, and contingent on the environment in which they co-evolved. As those experiences include social interactions, which in turn include more or less formal 'teaching' events, there can be no *absolute* division between the 'intuitive' and the 'taught', or between 'common-sense' and 'common knowledge'.

It is likely that some of our assumptions about *the way the world is* are developed early in life, before language is attained, and operate largely at a tacit level - as opposed to the easily verbalised 'alternative conceptions' that are normally elicited as simple statements representing propositional knowledge. These tacit understandings may have a wide influence on thinking, perhaps operating as regulators as new understanding is constructed. The term Gestalts has been used to describe these tacit assumptions (Anderson 1986, see §2.4.4).

§1.5.5: Epistemological learning impediments.

On the other hand, it may be useful to draw a distinction between learning impediments which may be seen to be *largely caused by the deliberate prior teaching of specific material* (§1.3.2), and those acquired through more nebulous experience. Research tells us that once established alternative conceptions may often be very stable, and may act as significant impediments to subsequent intended learning (§2.3.4). It is argued here that such alternative ideas may be equally effective as learning impediments, whether they are a learner's 'intuitive theory' or a 'misconception' of taught ideas. Yet the latter category of learning impediment may be avoidable in the future by appropriate changes to curriculum, text books and teaching schemes. It would therefore seem that if such impediments are identified, effort should be made to rethink our teaching approaches to see if we can avoid them in the future. I will refer to such SUBSTANTIAL LEARNING IMPEDIMENTS as EPISTEMOLOGICAL LEARNING IMPEDIMENTS.

So an EPISTEMOLOGICAL LEARNING IMPEDIMENT is an aspect of cognitive structure derived from deliberate formal instruction, yet which impedes subsequent learning. There has been much research into what I am calling ONTOLOGICAL LEARNING IMPEDIMENTS - alternative conceptions and frameworks developed prior to formal tuition. The lack of direct personal experience, the complex and abstract nature of theory, and the reliance on prerequisite learning could make chemical topics such as bonding fertile areas for researchers to uncover EPISTEMOLOGICAL LEARNING IMPEDIMENTS.

§1.5.6: Pedagogic consequences of learning impediments.

The four categories of learning impediment, and the ways that it is envisaged teachers should work to overcome them, are summarised in the table below:

type of learning impediment	nature of impediment	action required
deficiency impediment	no relevant material held in existing cognitive structure	remedial teaching of prerequisite learning (if available), or restructuring of material with bridging analogies *etc.*
fragmentation impediment	learner does not see relevance of material held in cognitive structure to presented material	teacher should make connections between existing knowledge and new material explicit
ontological impediment	presented material inconsistent with intuitive ideas about the world held in cognitive structure	make learner's ideas explicit, and challenge them where appropriate
epistemological impediment	presented material inconsistent with ideas in cognitive structure deriving from prior teaching	for individual learner: treat as ontological impediment; for future: re-think teaching of topic - order of presentation of ideas, manner of presentation, *etc.*

pedagogic consequences of the four types of learning impediments.

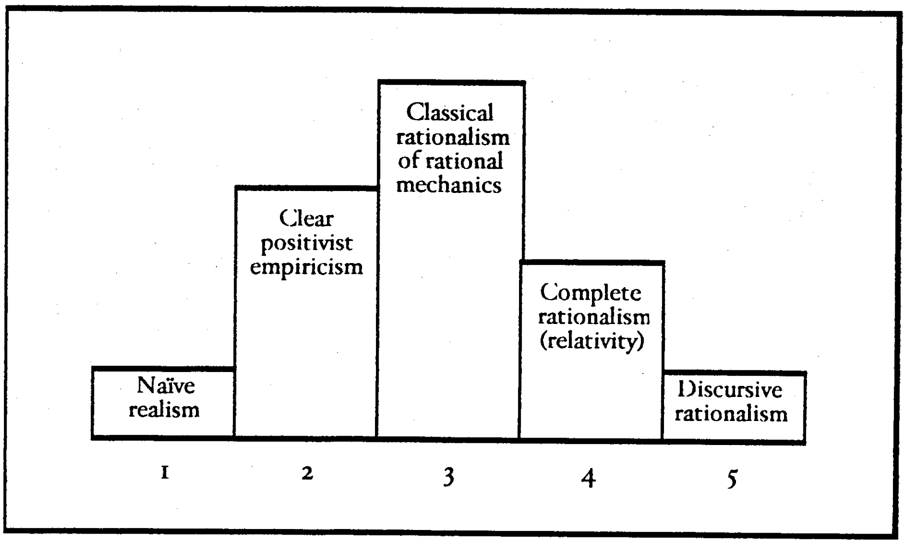
§1.6: Bachelard's *epistemological obstacles*.

The term EPISTEMOLOGICAL LEARNING IMPEDIMENT is similar to the French philosopher Bachelard's phrase *'epistemological obstacle'*. Bachelard had taught physics and chemistry at secondary level (Souque, 1988, p.9), and saw his first duty to his students to be to shake their preconceptions (Goldhammer, 1984, p.xxiv). Bachelard wrote as long ago as 1938 that "the adolescent enters the physics class with pre-conceived ideas", and that there was a need to "demolish the obstacles accumulated by daily experience" before desired learning could take place (quoted by Souque, 1988, p.9). Bachelard labelled these obstacles as 'epistemological', and by analysing historical scientific texts he identified a number of classes of such obstacles.

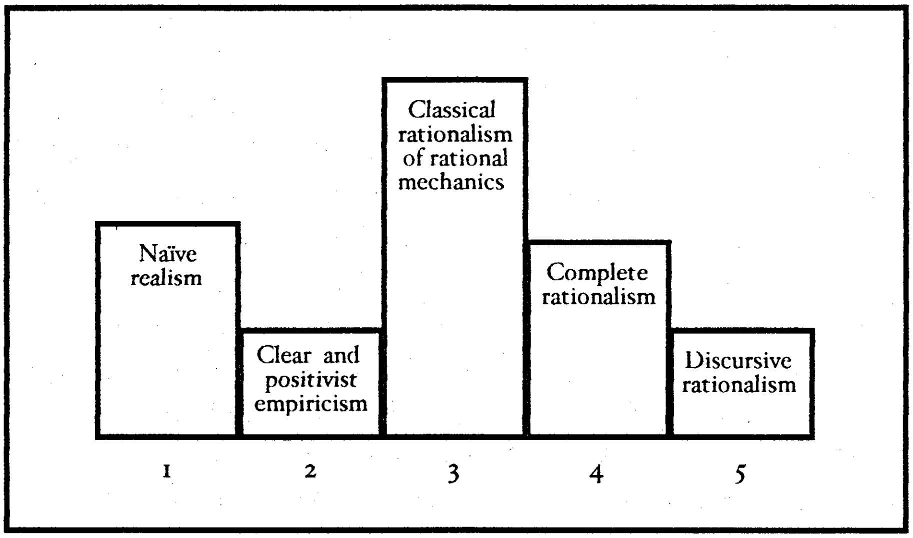
Souque lists five of Bachelard's categories of epistemological obstacles which relate to science teaching: immediate experience, generalising knowledge, the verbal obstacle, the animistic obstacle, and the obstacle of quantitative knowledge (pp.9-12). These 'obstacles' may be considered to be examples of what I have called SUBSTANTIVE LEARNING IMPEDIMENTS - aspects of cognitive structure that act as impediments to intended learning. Four of these categories, immediate experience, a tendency to generalise, a tendency to animism, and a tendency to allow quantification to stand for explanation, are related to my category of ONTOLOGICAL LEARNING IMPEDIMENTS, as they are ways of responding to the world which are not deliberately taught. Bachelard's *verbal obstacle* relates to the way that naming a phenomenon may provide a convenient label which stands in place of an explanation. This category also includes analogies and metaphors used in science, which may again stand in place of a deeper understanding. This type of obstacle is closer to my category of an EPISTEMOLOGICAL LEARNING IMPEDIMENT, particularly as Bachelard drew a distinction between the scientific mind - where a theory is understood, and *then* an analogy drawn - and the prescientific mind - where it is the analogy that is understood before the theory. This may be seen as a parallel for teaching analogies with the teacher and student representing the scientific and prescientific minds (c.f. §2.3.9 and §12.4.4).

A related aspect of Bachelard's work was his concept of an *epistemological profile*. Bachelard studied how scientific concepts had changed over time, and in particular how the historical development of a concept related to philosophical positions of varying sophistication (animism, realism, positivism, rationalism, and what Bachelard termed 'surrationalism' or complex rationalism and dialectical rationalism, Bachelard, 1968 {1940}, p.15). Bachelard thought that this sequence of philosophical positions was found across different scientific concepts - he wrote that "the direction of epistemological evolution is clear and constant: the evolution of a particular piece of knowledge moves towards rational coherence" (p.17). As he considered scientific progress to be the "one form of progress which is beyond argument", this sequence could represent "philosophical progress in scientific notions" (p.17). In practice different branches of science were at different degrees of "philosophical maturity", and so Bachelard characterised the philosophy of science as being "dispersed" or "distributed" (pp.10-11), and referred to "a multiplicity of philosophical explanations of science" (p.17). Bachelard believed that some physicists recognised the dialectical nature of their work. So, for example, he described (1984 {1934}, p.86) how Heisenberg included in the same book "two curiously antagonistic chapters": a critique of particle theory in terms of wave theory, alongside a critique of wave theory in terms of particle theory. Chemists, however, appeared to believe that the substances and reactions they studied were 'given' in nature rather than being the outcome of a ***dialogue with*** nature. Accordingly, Bachelard described chemistry as being "the elected domain of realists, of materialists, of anti-metaphysicians" (1968 {1940}, p.44).

Bachelard believed that although the concepts of formal public science progressed over time, in practice individual scientists did not exclusively apply the most sophisticated version of the concept. Rather the concept in the mind of the individual included aspects of the various historical versions, what he described as "...this plurality of meanings attached to one and the same concept..." (p.21). Bachelard demonstrated this by producing ***epistemological profiles*** - reproduced below - for his own conceptualisation of mass (p.36) and energy (p.38).



Bachelard's personal epistemological profile for 'mass'
(redrawn from Bachelard, 1968 {1940}, p.36.)



Bachelard's personal epistemological profile for 'energy'
(redrawn from Bachelard, 1968 {1940}, p.38.)

For Bachelard the ***epistemological profile*** represents evidence of ***epistemological obstacles***, that have acted historically, as the profile "bears the marks of the obstacles which a culture has had to surmount" (p.43). He thought that the earlier philosophical positions acted as obstacles to progress (p.37). As one of his translator's commented, Bachelard believed that

> "the prehistory of science (even its mythology), to the extent that it persisted in the structure of the human mind, needed to be exorcised - the Aristotelian, the Euclidian, the Newtonian, even the criticist spirit of Kant, leave structural layers in the human mind akin to the geological strata of the earth, and we need knowledge about these layers, self-knowledge and self-correction, before we can proceed." (Waterston, 1968, p.xi.)

§1.7: The notion of progression in learning chemistry.

I believe the three factors discussed above (§1.3) contribute to the limited amount of previous research into students' understanding of chemical bonding in the literature. These factors have therefore been taken into account in my own conceptualisation of, and approach to, the research problem. The nature of chemical concepts has been taken into account in my own thinking about how to define progression in learning chemistry. It is suggested that it is appropriate to think in terms of the learner developing a conceptual toolkit.

§1.7.1: Manifold models: the nature of some chemical concepts.

There are many studies in the literature that have examined learners' ideas in science by interviewing a range of individuals on one occasion each, comparing the learner's statements with accepted scientific ideas, and then listed and/or categorised the range of alternative ideas elicited.

For example Watts' analysis of interview data led to a set of frameworks that he constructed to make sense of learner's ideas about forces (1983a) and energy (1983b). As a physicist and experienced science teacher Watts had his own 'TEACHER'S SCIENCE' version of these concepts to act as a benchmark, by which he could judge whether learner's ideas were 'alternative'. (The use of descriptors such as SCIENTISTS' SCIENCE, TEACHER'S SCIENCE and CHILDREN'S SCIENCE has been suggested by Gilbert, Osborne and Fensham (1982) to distinguish the status of various science knowledge claims, §2.3.2). Further, as his study was not concerned with *progression* in *individuals'* understanding, Watts did not need to evaluate the relative merits of the various alternative frameworks uncovered.

It was suggested above that some concepts in chemistry may need to be considered in a different manner to physics notions such as force. It is generally agreed that there is a SCIENTIST'S SCIENCE concept of force even if the extent to which learner's ideas are expected to match the SCIENTIST'S SCIENCE varies considerably with educational level. I would argue that some key chemical concepts are more complex because the SCIENTIST'S SCIENCE concept is actually ***an amalgam of distinct and inconsistent models of variable applicability***. The notion of ***matching*** SCIENTISTS' SCIENCE becomes more problematic as it depends on specific context as well as educational level.

Driver has commented on the tendency to use a range of models of varying degrees of complexity in science,

> "In many areas of science, phenomena can be interpreted at a range of levels of sophistication, all of which are in some sense useful. ... [A] model [for electric current] is only 'better' than the previous one in that it accounts for a greater range of phenomena. A similar shift in the level of theoretical sophistication is encountered in several other topics, *for example, in chemical bonding*, the wave properties of light, inheritance and the molecular-kinetic theory of heat"
> (Driver, 1983, p.80, emphasis added.)

Driver here seems to be largely discussing models in CURRICULUM SCIENCE or TEACHERS' SCIENCE. Although the fluid flow model of electricity has been widely used as a teaching model, it has little currency in physics research, *i.e.* in SCIENTISTS' SCIENCE. In physics, electricity is understood in terms of a unified theoretical framework, based on accepted fundamental principles.

It has been argued in the past that in principle chemistry could be explained in terms of physics (§1.3.1). Scerri (1993) has considered the question of whether chemistry can be considered a reduced science - that is: can the problems of chemistry be reduced to applications of the principles of physics? Scerri points out that although *in principle* chemistry can be explained in terms of quantum mechanics: *in practice* the calculations are problematic in all but the most simple systems. That is, in practice, chemistry is something *other* than a branch of applied physics. Brock makes the same point when he claims that theoretical chemistry is "a quirky empirical science based upon a Schrödinger equation that can hardly ever be solved" (1992, p.505).

Zavaleta (1988) has noted how chemical 'facts' can not be seen in isolation from the theoretical framework in which they are discussed: he discusses several examples from the conceptual history of bonding theory, where "the meaning of a fact is inseparable from preconceived attitudes toward that fact" (p.680). Whilst this observation would apply to the *history* of all branches of science, where various paradigm shifts (Kuhn, 1970 {1962}) have occurred, in the case of chemical bonding Zavaleta has pointed out that chemists still currently use apparently incompatible theories to explain bonding, choosing the theory which is most successful for explaining the phenomenon in each case (p.677). He reports that the *best method* depends on the compound being studied (p.680). He concludes that,

> "It seems impossible to teach chemistry without misleading ourselves and our students to some, perhaps even a great extent. ... The conceptual history of bonding suggests that even the magnitudes of "accepted" facts do not exist apart from theoretical assumptions."
> (Zavaleta, 1988, p.680.)

Benfey has also argued that chemists can not understand the empirical data available in terms of a single theoretical framework,

> "sometimes [chemists] must live with two irreconcilable but complementary facts or theories because giving up one or the other member of such a pair would be false to our full awareness of the mystery of the natural world"
> (Benfey, 1982, p.398.)

The lack of a single unifying theoretical principle for chemistry leads to a profusion of models. Car (1984) suggests that in chemistry 'model confusion' is likely to be a more significant problem for learners than the existence of 'preconceptions',

> "students' difficulties in this area may be more usefully perceived in terms of confusion about the models used in teaching the concept rather than as a conflict between preconceptions and the scientific view"
> (Carr, 1984, p.97.)

Although his comments were based a consideration of the topic of acids and bases, he recommended further research in other chemical topics (Carr, 1984, p.103). As examples he posed the questions (p.103),

- are some problems about ions a result of carrying Daltonian and Newtonian models of atoms beyond their utility - since in those models atoms are unbreakable?
- are covalent bonding ideas served at all well by the Bohr model of the atom?

This present research may be seen - in part - as developing Carr's research programme into the curriculum area of chemical bonding.

Driver's comments above alert us to the succession of models through which learners acquire more sophisticated 'versions' of concepts such as 'electrical current', and suggest that progression in science learning could be understood in terms of the acquisition and mastery of successive models. My own analysis of the chemical bond concept (presented in appendix 4) led me to conclude that although there is a series of models of increasing sophistication, these are used as *alternatives* by chemists, rather than being seen as a sequential progression of teaching models which leads to the current SCIENTISTS' SCIENCE model of the chemical bond. This can be understood in terms of Scerri's observation that chemistry is not (yet) able to be reduced to physics. The expectation then is that Carr's 'model confusion in chemistry' is likely to extend beyond acid-base theory to topics such as the chemical bond.

§1.7.2: The toolbox analogy.

In terms of my own study, modelling progression in student understanding of the chemical bond is informed by the *alternative* acceptable models for bonding that are available.

The professional chemist, who has acquired and mastered the most sophisticated chemical bonding ideas, may nevertheless on occasions use a much more simplistic and limited concept of the chemical bond, because it seems more appropriate in some contexts. It would therefore be inappropriate to judge that a student lacks a more sophisticated perspective on bonding, simply because in the context of a certain research probe he or she selects to respond in terms of a more basic set of ideas.

To allow for this potential difficulty, I suggest that it is appropriate to conceptualise students' thinking in terms of the use of a toolbox of chemical concepts. The difference between the 'expert' chemist and the relatively 'naïve' student embarking on an A level course is that the novice does not have *alternative* strategies for when her G.C.S.E. (KS4) level understandings do *not* help explain the chemical data. As the student makes progress in the subject she will acquire more tools, and learn both how and when to apply them.

The G.C.S.E. 'graduate' has a 'toolbox' containing some useful chemical 'tools' to tackle a range of chemical 'jobs'. As students pass through an A level course they will continue to use these tools, but they will also meet many 'jobs' where their 'toolbox' does not provide them with a suitable instrument. The task of the teacher may be seen as to provide additional tools, and training in how and when the different tools should be used: a role which fits quite well with the idea of cognitive apprenticeship that has been discussed as a model for learning in science (§2.8.5). Some students will be more successful in acquiring the tools than others - success being measured not only in ownership of the tool (e.g. *describing* the rules of valence shell electron pair repulsion theory) but also in its appropriate use (e.g. *explaining and predicting* the shapes of simple molecules, but *not* trying to use it to explain patterns in ionisation energies - a job which requires a different tool). The practising chemist has a more extensive toolbox than the G.C.S.E. candidate, but still uses some of those same basic instruments. Different practising chemists carry with them, and use, different toolkits - they will have acquired different tools over their careers, and even perhaps discarded some that are not appropriate for the jobs they undertake.

I argue that this approach is a very powerful one, as it avoids the incorrect idea that more sophisticated understanding 'replaces' more basic ideas: in chemistry this is not always true - the more sophisticated ideas often supplement and complement the more basic ones. The tools I am discussing are mental tools: rules, laws, heuristics, models, representations *etc.*, they are tools from Popper's 'World 3' ("objective thought, especially *products* of the human mind", 1979, p.395), as are the chemical 'jobs' to be undertaken - explaining and predicting the properties and processes of nature. The phenomena to be explained are of 'World 1' (the "physical world", p.394): but our categories, and our explanations are mental constructions. As with other kinds of tools, these mental tools are not usually fully mastered at first acquaintance. In this research, an attempt was made to follow progression in terms of how and when a concept was used by a colearner.

In order to apply this analogy it is necessary to undertake an analysis of the topic area being studied. This task was undertaken early in the research, and the results are appended (as appendix 4). Appendix 5 presents a list of propositions that might represent expected prerequisite knowledge. In Appendix 6 the A level chemistry syllabus content most relevant to the concept of 'chemical bonding' is reproduced. In Appendix 4 the toolbox analogy is applied to the concept of chemical bonding. The likely extent of a successful learner's toolbox on entering A level study is presented, and then progression is considered in terms of how this toolbox might be extended and developed during an A level course. It should be emphasised that this analysis does not primarily *derive from* the research findings presented in chapters 6-11, but rather provides my own starting point for setting out on the analysis of my research data. In chapter 12 (§12.4) I will revisit this approach in the light of what was found out *during* the research.

§1.7.3: Overcoming learning impediments.

A typology of possible learning impediments was presented above (§1.5). Progression in learning about the chemical bond would require such impedimenta to be overcome. Successful acquisition of the conceptual tools of CURRICULUM SCIENCE would require the learner to hold the appropriate prerequisite learning in conceptual structure, to realise the relevance of new ideas to the existing knowledge, and to avoid or overcome the interference of existing alternative conceptions - whether derived from intuitive notions or developed from earlier formal learning. This may be illustrated through the example of learning about the concept of the polar bond.

§1.7.4: The polar bond: an example of an A level chemistry concept.

As an example to illustrate some of the points made above, consider the concept of a polar bond. This is not part of the 'toolkit' that my colearners brought to their A level studies (§11.6.2), but was part of the syllabus they were expected to study (appendix 6). It is a conceptual tool they are expected to acquire and be able to use.

In the examination syllabus (see appendix 6) this concept is listed with some related ideas (electronegativity; inductive effect; homolytic and heterolytic fission; nucleophilic and electrophilic attack respectively, on positive and negative centres in molecules).

A polar bond may be considered to be something intermediate between a covalent bond and an ionic bond. One way to model this is to use the simple idea of a covalent bond as a pair of electrons equally shared between two atoms, and to consider that in a polar bond the sharing is unequal. This may be conceptualised as the electron pair nearer one end of the bond, or with greater sophistication as an asymmetric electron density cloud. It is also possible to consider the polar bond as an ionic bond where the cation has polarised the electron cloud of the anion, as a resonance of the covalent and ionic forms, or as a molecular orbital which is asymmetrical between the two atoms due to the differences in the contributing atomic orbitals.

In chemistry bond polarity is said to be due to an electronegativity difference in the two atoms that are bonded. Electronegativity, in turn, can be related to the size of an atom, and its core charge (which is equal to the magnitude of the nuclear charge minus the number of shielding electrons).

The polar bond is clearly a concept that can be understood at a number of levels, of different sophistication, but all providing some insight. Understanding the polar bond assumes a knowledge of G.C.S.E. level chemistry (the covalent bond, the ionic bond, atomic structure in terms of charged particles, and electrons in shells), but is also related to other concepts such as electronegativity, core charge and orbitals that - like bond polarity itself - are also new to A level students. Understanding some aspects of the polar bond requires the learner to be familiar with some principles of quantum theory, which although actually a part of physics, are explicitly taught in A level chemistry (so the syllabus content in appendix 6 includes "elementary treatment of quantum numbers and atomic orbitals"). However, to make sense of some aspects of this content the learner also has to apply assumed prerequisite physics that may *not* be explicitly taught, in terms of basic electrostatics. The factors determining electronegativity of an element can be explained in Coulombic terms. The unequal sharing of the electron in a polar bond can be understood in terms of the equilibrium position reached when the electron pair is attracted to the two differently charged cores, but repelled by the other valence electrons. The notion of an electron pair itself requires the introduction of the idea of quantum-mechanical spin to explain why negatively charged electrons can be considered to pair.

Even from this brief discussion of one concept it is clear that progression in chemistry at this level requires the foundations of previous learning about chemistry and physics, the ability to switch between a range of models of varying levels of sophistication and abstraction, the ability to form chains of logical argument which work through various levels of explanation, and the acceptance of a theoretical structure where a range of - perhaps dimly understood - ideas are used to buttress one another.

The complexity of this concept suggests that whilst an individual lesson objective might be to *introduce* the idea of the polar bond, the desired understanding of the concept could only be a long term teaching goal: something to be developed though a careful process of gradual extension and reinforcement of learning. It also seems clear that in this example there is considerable scope for progress to be impeded. Consider the following hypothetical examples as an illustration:

- A learner who did not have assumed prerequisite knowledge about the electronic structure of the atom would not appreciate what was meant by the atomic core (a DEFICIENCY LEARNING IMPEDIMENT).
- A learner who did not appreciate the relevance of electrostatic principles learnt in school physics might not apply them to this chemical context (a FRAGMENTATION LEARNING IMPEDIMENT).
- A learner who accepted the division of chemical bonds into covalent and ionic as 'natural', reflecting a principle that nature exhibits dichotomies (perhaps such as metal/nonmetal; male/female; animal/plant; matter/energy), might not be able to accept the polar bond as a meaningful category (an ONTOLOGICAL LEARNING IMPEDIMENT).
- A learner who applied the learnt idea that 'similar charges repel' to the electrons in a bond without modification might only be able to visualise the electron distribution in the bond as one electron at each end (an EPISTEMOLOGICAL LEARNING IMPEDIMENT).

§1.7.5: Learners' ideas as learning impediments or cognitive resources.

It is clear from what has gone before that in this research learners' ideas about chemistry are seen as *potential* impediments to progress in studying the subject. However, this is not meant to suggest that learners' alternative conceptions should *necessarily* be seen as problematic. In the literature in chapter 2 it will be suggested that *meaningful learning* can only take place when the learner can relate new material to existing knowledge (see §2.2.5) - otherwise there will be a NULL LEARNING IMPEDIMENT. The learner's existing cognitive structure therefore acts as the resource base on which new understanding will develop. Research has suggested that a rich conceptualisation is an advantage in learning science (see §2.3.11). A learner's intuitive notions, or *mis*conceptions of the teacher's words, or recollection of a simplified explanation given by an adult, or even knowledge of some folk wisdom, could all potentially act as *either* SUBSTANTIVE LEARNING IMPEDIMENTS *or* the foundation for constructing an acceptable scientific understanding. The question of whether learners' alternative ideas should be considered as *barriers* or *bridges* in considered in the next chapter (§2.3.9).

§1.8: The longitudinal nature of this research.

To recap then, this thesis investigates the development of A level students' understanding of the concept of the chemical bond. This is one of the key concepts which is fundamental to the study of chemistry, yet there has only been a limited amount of research into the learning of this curriculum area. The present work addresses this deficiency, and takes into account the factors identified as possible reasons for the previous lack of attention.

Much of the early research into learners' ideas in science has been characterised as 'fishing expeditions' or 'butterfly collecting' (Watts 1988, Black, 1989). Such work leads to catalogues of learner's notions, but does little to explore the richness of learners' cognitive structures, or the manner in which thinking develops over time. In chemistry much of the work that has been carried out is of this form (Garnett et al., 1995). It is clear from my characterisation of chemistry concepts above that the present thesis describes an attempt to move beyond this.

The discussion of the concept of the polar bond (§1.7.4.) illustrates how concept learning at this level needs to be studied over a time-scale of months (or even longer, §12.4.2). A number of commentators have recognised that longitudinal studies are needed that follow the subtleties of individual's thinking over extended periods to examine issues of concept stability and development (Black, 1989, pp.3-4; Driver and Erickson, 1983, p.54; Driver, 1989, p.484; Gilbert and Watts, 1983, p.87; Howe, 1996, p.48; Watts, 1988, p.75).

The present thesis is based around a longitudinal research design where a limited number of learners were interviewed in depth over extended periods of time, with the aim of following development in understanding. These learners were volunteers, and were students of the researcher. This allowed a strong rapport to be developed, as the research was undertaken within the context of ongoing teacher-student relationships. This has a number of consequences for the research (§4.10.3). It brings advantages as I was able to bring insights from the classroom into the research sessions, and I was able to triangulate the findings from interviews against student course work (§4.9).

This approach also has other consequences for the research. For one thing, the teacher-researcher has responsibilities as a teacher. I had ethical responsibilities to my students to use the research interviews for their benefit: that is to provide them with useful feedback after research sessions. Indeed the students were conceptualised as *colearners* (§4.3.2) in the research. It would not have been appropriate for me to withhold feedback about, say, a significant misconception uncovered to find out whether it would be 'corrected' over time without my intervention (§4.10.3). However, it is not unusual in studies with an 'action-research' flavour for the desire to take action (i.e. improve educational practice) to compromise the study as 'pure' research (§4.1.2). In the present study the model produced in chapter 6 aims to identify factors which are significant in student progression. Had the intention been to produce some normative model of the average rate of student progress then the interventionist nature of the present research would have been a problem - but so would the small sample size, and the limited educational context. However, as is explained in more detail in chapter 4, the intention has been to develop grounded theory (§4.4). This theory - the model presented in chapter 6 and discussed in chapter 12 - is intended to be suitable for traditional hypothetico-deductive testing, but such testing is largely beyond the scope of the present work (although the *feasibility* of such testing is demonstrated in appendices 2 and 3).

A related issue is the question to which learning is something that occurs within a learner, or 'between' a learner and a tutor or peer. The influence of Vygotsky's ideas (§2.2.2), and the modelling of learning as a kind of cognitive apprenticeship (§2.8.5), suggest that any study which focuses on the what the learner can do in isolation ignores the normal context of learning (§4.10.4). From such a perspective the other minds with whom the learner interacts are key variables in the learning process, and the involvement of a teacher in a learning interaction is equally a *necessary* complication regardless of whether the teacher is also the researcher.

So the present study, then, develops a model of significant aspects in student learning about the chemical bond, based on detailed study of a limited number of learners in a particular institutional context, and taught by particular teachers, one of whom is also the researcher. The study is therefore undertaken in an idiographic tradition (§4.1.1) and this is reflected in the decision to present two detailed case studies of individual learners as part of the findings (i.e. chapters 7 and 8). The question of the generalisability of the findings outside of the specific context in which they were developed is considered in chapter 4 (§4.4, §4.10.5), and appendices 2 and 3 demonstrate the feasibility of testing the model against A level chemistry students in general.

§1.9: The structure of this thesis.

Following this introductory chapter, the remainder of this thesis is presented in eleven further chapters.

Chapter 2 presents an account of the field of constructivist science education research in which this present study is located. Chapter 3 reviews what was already known about student learning of chemical bonding. This chapter also considers studies into learning about the areas of prerequisite knowledge considered to be significant to avoid DEFICIENCY LEARNING IMPEDIMENTS. Chapter 4 explains the overall choice of methodology used in this study, and chapter 5 gives details of the data collection and analysis techniques used.

Chapters 6-11 present the findings of the research. Chapter 6 acts as an 'advance organiser' for readers, setting out the overall results of the study. Chapters 7 and 8 present case studies of individual learners, concentrating on their progression in understanding the chemical bond concept over time. Chapters 9 through 11 consider the three main themes which were identified through the data analysis as being most pertinent to developing understanding of chemical bonding.

Finally, chapter 12 discusses the findings of the study to consider the extent to which the initial research agenda set out in the present chapter has been addressed. In that final chapter suggestions for further research are made, and recommendations for changing the teaching of chemistry are presented.

Chapter 2.

Constructivism in science education.

§2.0: The alternative conceptions movement in science education.

> "there is an extensive literature that indicates that children come to their science classes with prior conceptions that may differ substantially from the ideas to be taught"
> (Driver, 1989, p.481.)

The present research has been undertaken within a tradition of work in science education which has been called the ***alternative conceptions movement***, (A.C.M.), or *constructivism*. This tradition has been recognised as a specific field of research, so that Gilbert and Swift suggest (1985, p.682) that the A.C.M. has the characteristics of a Lakatosian research programme (c.f. Lakatos, 1970), and Solomon (1994, p.7) refers to constructivism as a Kuhnian paradigm (c.f. Kuhn, 1970 {1962}). In a similar vein, Matthews refers to the influence of constructivism "as if a period of Kuhnian normal science has descended upon the science and mathematics education communities" (1993, p.363).

The term 'constructivism' has also been adopted by some to describe the much broader movement of workers undertaking qualitative, interpretative research (§4.1), as in contrast to what Beld has called "the conventional positivist paradigm in social science research" (1994, p.99, c.f. §4.1). However, when the term 'constructivism' is used in this present work it will refer to the tradition of research in science education, rather than the broader meaning. This distinction is significant as constructivism has been criticised (Matthews, 1994; Suchting, 1992), due to the strong relativistic stance suggested by some thinkers - such as von Glaserfeld's 'radical constructivism' (e.g. 1989) - which implies that learners' alternative constructions of science have as much validity as those of scientists. Although this is an interesting theoretical position, it is *not* one shared by most of the constructivists working is science education (although see §2.7 below), where an ethnographic approach may be used to elicit learners' notions, but where the usual aim (sometimes, but not always, made explicit) is to inform the teaching of accepted science as mediated by the science curriculum.

At the time of writing this thesis it is generally accepted that - as the motto above reports - children and students come to science classes with alternative conceptions about many aspects of science, and the constructivist view is that these 'interfere' with the intended learning of curricular material (or provide SUBSTANTIVE LEARNING IMPEDIMENTS in my term from chapter 1, §1.5.3). These beliefs are the basis for the "period of Kuhnian normal science" that Matthews refers to (1993, p.363). The possibility that the student has a 'blank mind' - the *tabula rasa* of a Baconian philosophy of science - is not considered tenable by constructivists (although research shows *teachers*' metaphors for the learning process are often quite compatible with it, {Fox, 1983; Tobin, 1990, pp.33-35}, and that almost half of student teachers surveyed thought that learners passively accumulate knowledge that is transmitted to them {Hennessy, 1993, p.8, and see also Linder, 1992}).

There is a vast literature on learners' understanding of science (Gilbert, 1994), as is shown by the review of research into children's ideas by Driver et al. (1994a). The bibliography 'Research on Students' Conceptions in Science' compiled by Carmichael et al. (1990) cites well over a thousand papers. Pfundt and Duit's bibliography includes 132 studies referring to chemistry topics, 208 in biology, and 740 relating to topics that are largely within physics (Duit, 1991, p.71).

It is only possible to refer directly to a small part of this body of work, and in this review I consider the literature which is most relevant to the present study. In this chapter I discuss the literature referring to the general theoretical framework which has been used to illuminate and define the field of enquiry. In the subsequent chapter I turn to what was already known about learners' ideas of chemical bonding prior to the research reported herein, and I consider several other topics where I argue that the learners' ideas have consequences for understanding the bonding topic.

§2.1: Cognitive structure, progression and learning.

In the previous chapter certain assumptions were made which are taken as axiomatic in the present study (§1.4). In summary: the existence of cognitive structure, its influence on the learner's behaviour (particularly verbal behaviour), and the ability to both construct and evaluate *models* of aspects of an individual's cognitive structure are all taken as reasonable foundations for the research.

These assumptions refer to something static - an individual's cognitive structure at one moment in time. The present study investigates ***developing understanding*** (§1.8), and is therefore concerned with changes in cognitive structure, and how they come about. In chapter 1 the concept of ***progression*** was considered, and was related to the nature of chemistry as a subject (§1.7). As this study concerns students who have been successful at G.C.S.E. level and are aiming to successfully tackle an A level chemistry examination, progression may be understood in terms of the expected appreciation of the bonding concept at these two examination levels, as in the analysis presented in appendix 4. It is in terms of such an analysis that learning may be judged as 'appropriate' or otherwise. Progression therefore involves such 'appropriate' learning, which implies changes in cognitive structure: that is *changes* in *the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to her at any point in time, and the manner in which it is arranged* (§1.4.1).

§2.1.1: The learning process and learning impediments.

Chapter 1 also considered types of *learning impediments*: in other words reasons why a motivated learner placed in a teaching situation might ***not*** undertake appropriate learning. In terms of cognitive structures, this would mean that after instruction the learner's cognitive structure did not sufficiently match that intended. The simple typology of learning impediments presented may be seen to rest upon a major assumption: that is that *a key variable in the learning process is the individual's cognitive structure before teaching occurs* (e.g. Driver and Bell, 1986). In other words two learners faced with exactly the same lesson may learn differently from it, both quantitatively and qualitatively, depending on their existing arrangement of knowledge. This is one of the main assumptions of the constructivist position.

§2.1.2: Construction of knowledge.

Constructivism is a perspective on learning, which views learning as an active process (§2.1.2). That is, the learner is seen to be pro-active rather than being the passive recipient of given knowledge (e.g. Driver and Bell, 1986, p.448, Pope and Gilbert, 1983, p.194). People have a predilection to make sense of their environment, and to arrange their memories of perceptions in some sort of pattern that acts as a framework for making sense of future experience (e.g. Osborne and Wittrock, 1983, p.492). It is also assumed that the construction process takes place through a series of steps of limited size. Although the 'construction of knowledge' is meant literally, the metaphor with constructing buildings [sic] is often seen as useful. As with building a house, *building knowledge* may be said to require good foundations, appropriate scaffolding and care to put each brick firmly in the correct place in the structure.

§2.2: Historical influences on the constructivist movement in science education.

The origins of the constructivist perspective are ancient, and can be traced back as least as far as Plato and Socrates; through the use of parables by Jesus; to Rousseau's emphasis on (a) learning from actual experience rather than through verbal instruction and (b) the importance of the child's existing stage of development; and to Dewey's perception of the 'organic' nature of knowledge (Clark, 1968, p.181, p.187-8; Egan, 1984, pp.28; Evetts, 1973, p.33; Russell, 1961 (1946), p.775). Dewey's view was that education should be learner-centred and that knowledge was something people constructed (Evetts, 1973, p.33; Hyland, 1993, p.94).

Among more modern thinkers constructivism in science education has been influenced by the work of psychologists such as Piaget, Kelly, Vygotsky, Bruner and Ausubel.

§2.2.1: Piaget.

Jean Piaget is best known for proposing his 'stage-theory' of development, which has been widely reported (for example, Beard, 1969; Crain, 1992). Brown summarises this 'ages and stages' approach as "children of a given age are more likely to demonstrate similarity of [mental] structures that children of different ages" (1977, p.82), although he points out that this is just one aspect of Piaget's overall theory of genetic epistemology (i.e. the development of knowledge). *Stage theory* has been immensely influential, for instance as a starting point for workers attempting to match the science curriculum against what can reasonably be expected of learners at different ages (e.g. Shayer and Adey, 1981). So, the suggestion that only about 50% of people ever achieve Piaget's highest stage of formal operations (Arlin, 1975, p.605) would have serious implications for what can be effectively taught in science classes. The Piagetian stages were intended to operate across all areas of knowledge regardless of context, and this has been heavily criticised (for example see the discussion in Bliss, 1993). Piaget himself recognised that although the stages might in part reflect a maturation of the nervous system, this would only provide a potential which required experience of the physical environment and social interaction ("the educational influences of a favourable social environment") for its realisation (Inhelder and Piaget, 1964, p.5). The present study is not framed within this stage-theory tradition, and I will not elaborate on this argument here. However, one aspect of the debate is relevant.

Some workers have suggested that there should be a 'fifth stage' beyond formal operations, which might be considered to relate to mature adult thought (Arlin, 1975; Kramer, 1983). If this were truly a stage in the Piagetian sense it could only be attained by those that had successfully passed through the stage of formal operations. This would be significant because the proposed characteristics of such post-formal thinking are that: (a) knowledge has a relativistic, non-absolute nature; (b) contradiction is accepted as part of reality; and (c) the integrative approach to thinking is a central feature (Castro and Fernández, 1987, p.443). Kincheloe refers to "modes of thinking which transcend the formal operational ability to formulate abstract conclusions, understand cause-effect relationships, and employ the traditional scientific method to explain reality" (1991, p.44). Riegel has argued that tolerance of ambiguity reflects a more developed cognitive stage, so that dialectical operations is a stage beyond formal operations (Buck-Morss, 1980, p.130). It would seem that this is just the kind of thinking that may be needed to cope with a subject such as chemistry where the learner must learn to accept a range of partial, complementary - and sometimes inconsistent - models (§1.3.1, §1.7.1). *If* the sequential stage-theory approach were to be accepted, then we might expect that many A level students would not cope with such a subject as chemistry. However, those who *reject* the Piagetian stages would consider that there is no reason to believe that most learners can not develop 'post-formal thinking'.

The two aspects of Piaget's work which are particularly relevant are his *methodology* and the *nature of his data*. Piaget developed an approach of using clinical interviews such that "each child's thought patterns are traced by a series of questions, each being dependent upon the the previous response given by the child" (Brown, 1977, p.89). Such an approach was later taken up within the alternative conceptions movement (§4.6). Piaget published extensively, including details of some of the speech utterances of his young subjects. These data illustrate that the young child's thinking about the world may seem illogical, irrational and even contradictory to adults. In particular, Piaget highlighted the animistic and anthropomorphic nature of much of the reasoning of young children (discussed further in chapter 3, §3.1.4, and appendix 7, §A7.6). Further, they illustrate that children who have not undertaken formal instruction may still have constructed their own ideas about phenomena they experience in the world, and their own meanings for words as they acquire language (e.g. Piaget, 1973 {1929}). Piaget wrote of the 'myth' of the sensory (or even perceptual) origins of scientific knowledge, and emphasised that the role of intelligence was to 'transform'. He believed that knowledge is formed by operating on perceptions with logico-mathematical frameworks (Piaget, 1972 {1970}), that is aspects of existing cognitive structure (§1.4.1). These are key concerns for the science education community, and a focus for research within the constructivist tradition (c.f. §2.1.3).

Pope and Gilbert (1983) have commented on the constructivist assumptions inherent in much of Piaget's work (p.195.) and have described the "essence" of Piaget's epistemology as being "constructivist and relativist" (p.196). The active role of the learner as constructors of knowledge in Piaget's work has also been recognised by Driver and her coworkers (e.g. Driver and Easley, 1978; Driver et al., 1994c, p.3).

§2.2.2: Vygotsky.

Piaget, then, assumed that the learner was an active constructor of knowledge, and his perspective focuses on *the learner's actions on his or her environment*. Vygotsky was contemporaneous to Piaget, but considered *social interaction* to be a central part of learning. Whereas Piaget's research programme was one of *genetic epistemology* (finding the cognitive-development sequence that each individual person would be expected to pass through), and took the view that "development explains learning" (Piaget, 1964, p.176), Vygotsky's programme was *sociohistorical*, that is it took the perspective that human psychological developments are mediated by culture and contingent on history (Cole, 1990, p.91). Vygotsky believed that from the age of about two years development is closely influenced by the young learner's interactions with other minds (Crain, 1992, p.199, p.211).

Vygotsky focuses on word-meaning as a useful unit for analysis (believing this to be the "unit of verbal thought that is further unanalysable and yet retains the properties of the whole", Vygotsky, 1986 {1934}, p.5). He pointed out that a word represents a generalisation (p.6). Fodor (1972) has suggested that Vygotsky's central thesis was that *word meanings evolve as the child develops* (p.86). For Vygotsky words were tools of thought (Vygotsky, 1986 {1934}, p.107), and were the *essential* tools for higher level thinking (p.251, Newman and Holzman, 1993, p.132), so that "real" concepts were not possible without them (Vygotsky, 1986 {1934}, p.107).

For Vygotsky, language was *the medium* in which teaching takes place, and from which the learner constructs a way of thinking (Edwards and Mercer, 1987, p.20). Vygotsky considered thought and speech to have different *origins*, but thought that the acquisition of words through speech provided the tools for conceptual thinking to develop (Vygotsky, 1986 {1934}, p.83).

In the present study it is assumed that the concepts of interest (such as electronegativity) can be represented by words (such as 'electronegativity'). Vygotsky points out that word meaning is tied to the context of use (p.245). The main data collection technique used in this study is the interview: so that colearners are asked to formulate their thinking using words, and those words are recorded, transcribed and analysed. Vygotsky's focus on words and word-meanings will inform the type of transcription considered appropriate for the present research (§5.2.1).

Vygotsky's analysis was undertaken from a perspective which recognised the social context in which learning and development take place (Edwards and Mercer, 1987, p.19). He recognised word meaning as the unit of the social interchange that was itself central to development of higher cognitive functions (Vygotsky, 1986 (1934), pp.7-9; 1978, p.57, p.88.) Like Piaget (§2.2.1), Vygotsky saw 'internalisation' as a process whereby an originally external operation becomes "re*constructed*" within the mind of the individual (Vygotsky, 1978, p.56), and he emphasised that teachers could could lead pupils to higher levels of conceptual understanding than they would otherwise achieve (Edwards and Mercer, 1987, p.20).

Perhaps because of his focus on the social context of learning Vygotsky was interested in how learners solved problems when assisted by adults, compared with their competence when working alone. Independent working - "without the assistance of others, without demonstrations, and without leading questions" (Vygotsky 1978, p.88) is - from an educational perspective - a contrived situation, and Vygotsky put emphasis on the extent to which a learner could extend beyond their unassisted performance when provided with suitable cues. Bruner (see below, §2.2.3) has developed this perspective and considers that the teacher acts "as a vicarious form of consciousness" whilst the student is mastering a new skill (Hennessy's, 1993, p.13).

Vygotsky introduced the term 'the zone of proximal development' (or Z.P.D.) to describe the sphere of activity where a learner could solve problems with the teacher's guidance, or in collaboration with peers, but ***not*** independently (1978, p.86; 1986 {1934}, p.187). He thought the Z.P.D. was a better indicator of intellectual potential than mental age itself (1986 {1934}, p.187). It is within the Z.P.D. that control of cognitive functions is transferred from the interpersonal plane to become truly intrapersonal (Newman and Holzman, 1993, pp.66-67), so that what the learner can achieve within the Z.P.D. with assistance, is what he or she will next be able to achieve unaided (Crain, 1992, p.215).

In the present research much of the data derives directly from such a context of teacher-colearner dialogue, and it is accepted that through the research process the colearners may indeed be led to new levels of conceptual understanding. For an example, appendix 8 presents an extract of interview transcript where colearner Noor constructed a case for expecting interactions between neutral molecules (i.e. what are known to chemists as van der Waals' forces). However rather than see this as an unfortunate intervention that perturbs the subject of the study, it is seen from a Vygotskyan perspective as the natural context of concept development. Some methodological approaches would suggest that the interviewer should not provide cues when attempting to find out how much the learner understands. Yet a Vygotskyan perspective might suggest that an approach which provided a scaffold within the learner's Z.P.D. might ultimately be more revealing. This point is considered more at the end of chapter 4 (§4.10.4).

Of particular importance for constructivism is the distinction Vygotsky makes between two classes of concepts that he terms *spontaneous*, those which "emerge from the child's own reflections on everyday experience", and those he labels *scientific* and which the learner meets through formal instruction (Kozulin, 1985, pp.xxxiii-xxxiv) - whether in science or any other part of the curriculum (Newman and Holzman, 1993, p.61). These latter concepts tend to be given verbal definitions and are taught explicitly, unlike *spontaneous* concepts (Newman and Holzman, 1993, p.61). Although *spontaneous* concepts do not necessarily *remain* tacit, the distinction in *origin* is very significant for Vygotsky,

> "The child becomes conscious of his spontaneous concepts relatively late; the ability to define them in words, to operate with them at will, appears long after he has acquired the concepts. He has the concept (i.e., knows the object to which the concept refers), but is not conscious of his own act of thought. The development of a scientific concept, on the other hand, usually *begins* with its verbal definition and its use in nonspontaneous operations - with working on the concept itself. It starts life in the child's mind at the level that his spontaneous concepts reach only later."
> (Vygotsky 1986 {1934}, p.192.)

Vygotsky believed that *conceptual development* involved a process of convergence as the concrete becomes abstracted, and the abstract is made concrete (1986 {1934}, p.193). Over time *spontaneous* concepts would acquire a formal structure and be open to conscious use, and formal *scientific* concepts would evolve connections with real experience (1986 {1934}, p.194) - indeed *scientific* concepts provide the frameworks within which a learner could become aware of his tacit *spontaneous* concepts (Crain, 1992, p.213). Vygotsky then presupposed the presence of cognitive structure,

> "Concepts do not lie in the child's mind like peas in a bag, without any bonds between them. If that were the case, no intellectual operation requiring coordination of thoughts would be possible, nor would any general conception of the world. Not even separate concepts as such could exist; their very nature presupposes a system."
> (Vygotsky 1986 {1934}, p.197.)

For scientific concepts the 'structures' made up a system (Vygotsky 1986 {1934}, p.205), and the meaning of the concept depended on its relationship to other concepts in the system (c.f. §2.10.2). One of the techniques used to collect data in the present research was concept mapping, which attempts to make explicit just this aspect of concepts (§4.9.1).

§2.2.3: Bruner.

Vygotsky's work has been disseminated and developed by Bruner (e.g. Crain, 1992, p.220), who concludes from studies of language acquisition in infants that in general people tend to have similar forms of mental organisation (1987, p.87, c.f. §1.5.4). Bruner worked from Vygotsky's (1986 {1934}) observation that communication between minds had to be indirect, and took place through language; and in particular that thoughts had to be translated into words (p.252). Bruner (1987) sees our shared use of language as a means of ensuring that we are sharing meaning, that is of "constant transactional calibration" (p.87) so that we can understand one another's minds and one another's worlds (p.88). Usually in conversation we understand what the other is saying, and - if not - we are usually aware of this, and have accepted ways of checking on meanings - i.e. what he has described as ways of "calling for repairs in one another's utterances to assure such calibration" (p.87).

This is an assumption that is built into the present research: that it is possible to understand my colearners' ideas about chemistry by interviewing them. This may seem an obvious point, and perhaps even trivial. However, Kuhn has referred to different paradigms as being incommensurate: in other words providing no basis for comparison. This position has been taken to mean that scientists working within two different scientific paradigms can not discuss the relative merits of their position in any objective way (Phillips, 1987, p.22). This would be very serious for the present work as it would mean that a teacher could not persuade students holding alternative frameworks about science that their views were in error as there would be no common basis for a rational discussion. Popper (1994) has referred to this as ***the myth of the framework***, that is that "a rational and fruitful discussion is impossible unless the participants share a common framework of basic assumptions or, at least, unless they have agreed on such a framework for the purpose of the discussion" (pp.34-5). Popper criticises this 'myth' (1970, p.56), although he accepts that it "contains a kernel of truth" (1994, p.35).

Although Kuhn himself originally referred to paradigms as incommensurable (1970 {1962}, p.103, p.112, p.157), he objected to the interpretation that this meant there could be ***no*** communication between scientists working in different paradigms, and argued that he had clearly implied that communication would be "only partial" (1970 {1969}, p.198). Kuhn later reformulated this "incommensurability of viewpoints and ... partial breakdown of communication between the proponents of different theories" in terms of people speaking "different languages". For Kuhn these different languages expressed different cognitive commitments, and were suitable for *different worlds* (1977, pp.xxii-xxiii). Kuhn pointed out that different languages divide up the world in different ways, and so that translation between the languages (and therefore worlds) of two speakers would inevitably involve some change in meaning (1970 {1965}, p.268): thus the ability to grasp another's viewpoint is not absolute, but "inevitably limited by the imperfections of the process of translation and of reference determination" (1977, p.xxiii). Nevertheless, from Bruner's perspective two participants from different backgrounds can move towards co-constructing a dialogue through their attempts to converse.

Indeed the process of undertaking research interviews, and analysing the data, described in this thesis (chapters 4 and 5) is primarily about overcoming these limitations of the *'imperfections of the process of translation and of reference determination'*. But as Bruner points out: in dialogue, language is used to provide *constant transactional calibration*, so it will be assumed that to some extent my colearners and I (as experienced language users) have developed skills in interpreting the 'worlds' of others. Or as Polanyi put it, "to speak is to contrive signs, to observe their fitness, and *to interpret their alternative relations*" (1962 {1958}, p.82, my emphasis).

From Popper's (1994) perspective, although conversation may be *easier* between two people who share common 'frameworks' of assumptions, it is potentially less fruitful in the sense of how much the discussants can learn from the dialogue (p.35). This is an important point for the present research where the colearners and myself started from the perspective that their understanding of chemistry was different to mine, and both parties thought it would be useful to learn more about this difference. That I was aware of the literature about alternative conceptions, and something of Kuhn's notion of paradigms, where my colearners probably perceived the context of the interviews in terms of 'deficiencies' in their knowledge compared to mine, does not detract from this. Both parties to an interview accepted that there were different understandings to explore, and were committed to using language to undertake the exploration. This is part of the rationale of referring to my interviewees as *colearners* in the research (§4.3.2).

Bruner is known for his work on developing the theory of instruction, and in particular for proposing the importance of 'guided discovery' (Fox, 1993, p.181). Bruner believed that the cultural invention of schooling led to new ways of thinking (Carraher et al., 1991, p.234; Wood, 1988, p.15, p.84; Wood, 1991, p.97), and that schools should be primarily concerned with developing thinking and problem-solving skills in the academic disciplines rather than imparting specific knowledge (Fox, 1993, p.182; Wood, 1988, p.8, p.136). Bruner (1979 {1962}, p.87) believed that discovery methods encouraged children to become constructivists and effective learners.

Bruner describes three levels of representing the world (Bruner, 1977 {1964}, p.208; see also for example Brown, 1977, p.74; Fox, 1993, p.182): the enactive level (through action), the iconic level (through mental imagery) and the symbolic level (through the manipulation of symbols), and he suggests that teaching that starts with the symbolic level will lead to rote learning (c.f. §2.2.5). Bruner's ideas may be seen to draw upon both Piaget (§2.2.1) in that we create knowledge by active restructuring of our experience of the environment (Child, 1986, p.110; Wood, 1988, p.183), and Vygotsky (§2.2.2), with knowledge presented at the symbolic level being akin to *scientific concepts* that need to be integrated with *spontaneous concepts*. Bruner has recommended the use of a 'spiral curriculum' where the same material is met at increasing levels of difficulty during a learner's school years (Child, 1986, p.363).

The research reported in the present thesis does not explore the formal teaching that learners received during their A level course, but Bruner's ideas are considered significant to the collection of research data. Bruner has explored the Vygotskian notion of the Z.P.D., and his group suggested the notion of *scaffolding* (Tharp and Gallimore, 1991, p.48) whereby a learner is guided by an adult, but the degree of support is reduced as the learner is gradually able to undertake the task without assistance. The teacher acts as "a vicarious form of consciousness until such a time as the learner is able to master his own action through his own consciousness and control" so that the learner can "internalise external knowledge and convert it into a tool for conscious control" (Bruner, quoted in Meadows, 1993, p.248). Bruner introduced the 'hand-over' principle: that the learner moves from being an observer to a participant (Rogoff, 1991, p.78; Tharp and Gallimore, 1991, p.50),

> "One sets the game, provides a scaffold to assure that the child's ineptitudes can be rescued by appropriate intervention, and then removes the scaffold part by part as the reciprocal structure can stand on its own."
> (Bruner, quoted in Wood, 1991, p.109.)

One of Bruner's coworkers has suggested that "it is hard to find problems that are impossible for a child, given some coaching and some external aids" (Olson, quoted in Brown, 1977, p.78), and another emphasises that "built well, such scaffolds help children to learn how to achieve heights that they cannot scale alone" (Wood, 1988, p.80). Although the details of the scaffolding process will vary, the principle is considered to be applicable to learners across a wide age range (Wood, 1991, p.110).

The research interviews undertaken in the present research used probing questions that might well have acted as scaffolding to allow my colearners to move beyond explanations that they could have produced spontaneously. The methodological consequences are discussed in chapter 4 (§4.10.4) - where it is considered that from a Vygotskian perspective it is quite appropriate to explore the students' Z.P.D.s.

§2.2.4: Kelly.

Whereas Piaget demonstrated how children's thinking could be so different to that of adults, and Vygotsky emphasised the importance of language as a mediator that led to convergence of understandings within a culture, Kelly's work highlighted how each person's cognitive structure is distinct.

Kelly built a theory of personality that he called 'personal construct theory' (P.C.T.) He described his position as 'constructive alternativism', which emphasised the way an individual's knowledge was provisional (Kelly, 1963, p.15). Kelly's system assumed learning was on-going and central to personality (p.75). A person's way of relating to their world could be understood in terms of their *personal construct system*. Constructs were not to be seen as so different from concepts, (pp.69-70), but Kelly thought it was productive to construe them as bipolar or dichotomous (Bannister and Fransella, 1986, p.12; Kelly, 1963, p.59), that is, as the basis for making discriminations (Bannister and Fransella, 1986, p.21).

It would seem that Kelly's constructs were not limited to Vygotsky's 'scientific' concepts where words may be used as tools, but also included 'spontaneous' concepts (c.f. Kelly, 1963, p.92) which were not labelled by words or other symbols (p.110).

Driver and Easley (1978), and Gilbert and Swift (1985) have in different ways attempted to define the constructivist movement in science education in *contrast to* aspects of Piagetian research; and the former authors have also emphasised the significance of Piaget's methodology for (what in 1978 was) the new tradition of investigating 'alternative frameworks' (p.62). However it is the ideas of Kelly which have been used most explicitly as the theoretical basis of the field of enquiry. This is largely due to the work of the 'Personal Construction of Knowledge' group at Surrey University (Gilbert, Pope, Watts and others) who used Kelly's Personal Construct Theory as the basis of their position on the nature of concepts and concept understanding (Watts et al., 1982, abstract). Concepts would not be viewed as logically organised and tightly defined as in a text book, but to be more ephemeral (or perhaps in a currently in vogue term, 'fuzzy') akin to a "fund of expectations" (p.8.) and "the adoption of a point of view" (p.9) (see §2.10.2, below).

Kelly's work was even more significant for providing the *epistemological* position of 'constructive alternativism', that individuals construct models of their environment, based on tentative hypotheses, which are tested against experience and modified as required (Pope and Gilbert, 1983, p.196-7).

Kelly's central metaphor was of *man-the-scientist* (1963 {1955}, p.4), and this was reflected in Driver's focus on the pupil-as-scientist (Driver and Erickson, 1983; Driver, 1983). Driver referred to pupils' construct systems as "spectacles of their own preconceptions" which - in my terms - may act as SUBSTANTIVE LEARNING IMPEDIMENTS. That is, that many learners "have difficulty in making the journey from their own intuitions to the ideas presented in science lessons" (1983, from the preface). She compared this 'journey' to "paradigm shifts in their thinking" (p.9) and noted how some of the children's ideas were similar to historical scientific ideas (p.76), something that had previously been noted by Piaget (Driver and Easley, 1978, pp.75-76).

An important aspect of Kelly's theory for the present research is that it considered the issue, discussed above (§2.2.4), of how communication can occur between people holding disparate models of the world. Kelly thought that differences in the construct systems of two individuals could be overcome by the ability of individuals to 'construe the construct system of the other' (Pope and Gilbert, 1983, p.197). In other words, one may develop one's construct system to include a model of the other's version of the world: it is possible to build into one's cognitive structure not only models of how one construes the world, but models of how one construes others to model the world. Examples might include scientists working in two different Kuhnian paradigms, a historian trying to understand the phlogiston theory, or a science teacher trying to make sense of his learners' ideas.

Despite the emphasis on Kelly's ideas, his *methodology* has not tended to feature in research in learners' ideas. In chapter 4 I discuss why this is, and how I incorporated some of Kelly's methodology - the construct repertory test - into my own research (§4.7).

§2.2.5: Ausubel.

Another psychologist who influenced the A.C.M. was Ausubel, who was known for his adage that one should find out what a learner knows, and teach accordingly. Ausubel introduced the notion that learning needed to be *meaningful* (c.f. rote), and this depended on the learner's cognitive structure, and the nature of the material to be learned (Ausubel, 1961, p.18; Ausubel and Robinson, 1969, pp.50-51). Ausubel and Robinson suggest three conditions for meaningful learning to occur:

> (a) The material itself must be relatable to some hypothetical cognitive structure in a nonarbitrary and substantive fashion.
> (b) The learner must possess relevant ideas to which to relate the material.
> (c) The learner must possess the intent to relate these ideas to cognitive structure in a nonarbitrary and substantive fashion.
> (Ausubel and Robinson, 1969, p.53.)

Whilst the third item, which relates to motivation and metacognition, is important, it is the former two points which are of most concern here (c.f. §1.5). Firstly if new material presented to a learner is not able to be related to his or her existing knowledge (i.e. the conditions for a NULL LEARNING IMPEDIMENT as discussed in chapter 1, §1.5.2) it can not be learnt in a meaningful way, and must be learnt by rote if it is to be learnt at all. In Ausubel's terms, the learner is not "able to effectively exploit his existing knowledge as an ideational and organizational matrix for the incorporation, understanding, and fixation of large bodies of new ideas" (Ausubel and Robinson, 1969, p.57). Secondly, if meaningful learning implies some form of integration or assimilation with existing knowledge, then if the existing knowledge is contrary to that of the authority (teacher, textbook etc.) the new material will not be understood in the way intended (i.e., in the terms presented in chapter 1, there will be a SUBSTANTIVE LEARNING IMPEDIMENT).

Such a view leads to an approach to teaching that emphasises the importance of, and seeks to build upon, the learner's existing ideas; rather than marginalise them and assume that they will be overwritten by instruction. It was this perspective that led to the development of the field of research in which this study is located.

§2.3: Children's science.

A learner's existing cognitive structure may therefore be considered a major variable in any learning episode. The A.C.M. developed as a research programme concerned with investigating what ideas learners were bringing to science classes.

§2.3.1 Preconceptions, misconceptions and alternative frameworks.

It is appropriate that Driver's words should stand at the head of this chapter, as one of the seminal papers in the field was published by Driver and Easley in 1978. Their paper began with an extract from two fourteen year old pupils discussing thermal expansion, and referring to the *molecules expanding*, and to the 'heat molecules' (c.f. §3.1.2). Driver and Easley asked about the status of such statements: whether they were "misconceptions, errors, partial understandings or misunderstandings?" (p.61).

They make a reference to the ideas of Ausubel (see above, §2.5.5), who would label such ideas as 'preconceptions', but they felt that the term did not acknowledge how such notions could have the status of models and theories (p.62). The alternative term 'misconception' implied a misunderstanding of formally taught material, and excluded intuitive theories - "the situation in which pupils have developed autonomous frameworks for conceptualising their experience of the physical world" (p.62): i.e. in my terms it recognised EPISTEMOLOGICAL LEARNING IMPEDIMENTS but not ONTOLOGICAL LEARNING IMPEDIMENTS (c.f. §1.5.3-5). They suggested instead the more inclusive term ***alternative frameworks.*** Alternative frameworks referred to conceptual frameworks which led to the accepted science being counter intuitive, or significantly different to the learner's ideas (Driver, 1983, p.3).

Pope and Gilbert recognised that the notion of 'alternative frameworks' could be related closely to Kelly's P.C.T. (see above, §2.2.4), where each learner held a unique, and dynamic system of personal constructs (Pope and Gilbert, 1983, p.197). However, as will be discussed below (§2.4.1), the absence of agreed terminology in the field has led to misunderstandings about exactly what different workers mean by terms such as 'alternative frameworks'.

§2.3.2: The notion of *children's science.*

At the time of writing their paper Driver and Easley were able to describe naturalistic studies based on clinical interviews as "usually small scale and scattered" (1978, p.77). However by 1983 Driver and Erickson referred to a "growing interest" in this work (p.38-39, see also Gilbert and Watts, 1983, p.61). For example the *Learning in Science Project* which ran from 1979 to 1984 at the University of Waikato, New Zealand (Osborne, 1980), and work based at the University of Surrey made extensive use of these techniques.

One such study was a 1982 paper by Gilbert (Surrey, U.K.), Osborne (Waikato, N.Z.) and Fensham (Monash, Australia) which prominently used the term 'CHILDREN'S SCIENCE' to describe the "conceptual structures" which children used to understand the world prior to formal instruction (p.623, p.627), and could therefore lead to what I have labelled ONTOLOGICAL LEARNING IMPEDIMENTS.

Gilbert et al. contrasted CHILDREN'S SCIENCE with SCIENTISTS' SCIENCE - the consensual scientific view of the world and meaning for words (p.627) - and with TEACHERS' SCIENCE - which was different again, but could usually be considered to fall somewhere between the two (pp.627-8). Gilbert et al. also recognised that the 'viewpoint presented' in science classes matched none of these, and was the result of TEACHERS' SCIENCE being mediated through the presentation of the curriculum (p.628). This 'viewpoint presented', which is the teacher's interpretation of the curriculum in view of his or her own understanding of science, I will for consistency refer to as CURRICULUM SCIENCE.

§2.3.3: The range of *children's science*.

Research soon demonstrated that children brought their own alternative ideas to the classroom relating to most, if not all, areas of the science curriculum (Driver, 1983, p.7). Driver directed the *Children's Learning in Science Research Group* (CLiS Project) at Leeds which set about investigating CHILDREN'S SCIENCE in a range of curriculum topics (as well as developing constructivist teaching schemes for some), and in 1994 Driver and coworkers published a review of research into children's ideas which covered many aspects of secondary school science.

§2.3.4: The implications of *children's science*.

In 1982 Nussbaum and Novick reviewed the 'numerous reports' on alternative frameworks and concluded that almost all suggested that such frameworks interfered with intended learning (p.184). Ault, Novak and Gowin (1984), studied learners' notions of the *molecule* concept working with the same individuals on two occasions (in second grade, and then in seventh grade) and concluded from their study that the differences in the conceptions in the early grade were significant for later understanding, and that the learners' meanings as grasped in primary grades would effect their understanding years later (p.459).

Given that research suggests that the learner's existing cognitive structure has a major influence on what is learned, and how it is learnt, it becomes important for teachers to know about, and take account of, the ideas learners bring to class. Driver and Erickson set out their *empirical premises* in 1983 (p.39):

- *Many students have constructed from previous physical and linguistic experience frameworks which can be used to interpret some of the natural phenomena which they study formally in school science classes.*
- *These student frameworks often result in conceptual confusion as they lead to different predictions and explanations from those sanctioned by school science.*
- *Well-planned instruction employing teaching strategies which take account of student frameworks will result in the development of frameworks that conform more closely to school science.*

Gilbert et al. (1982) considered the possible outcomes of the interaction of CHILDREN'S SCIENCE with CURRICULUM SCIENCE There is a spectrum of possibilities. At one extreme the learners' ideas may be readily displaced by exposure to teaching. At the opposite pole the student frameworks might be so stable that they were completely unaffected by teaching. Either of these possibilities would reduce the whole issue to a purely academic one rather than a matter of serious practical concern for science teachers. (It may also be pointed out that in evolutionary terms it would not be expected that a learner with *totally* labile or *totally* stable cognitive structure would survive to evolve under natural selection: in one case the individual could never learn from new experience, and in the other case the individual would have no stable basis for predicting the future, or planning actions. We would expect evolution to result in the selection of some intermediate situation that was optimal in the environmental conditions where selection operated).

Gilbert et al. discussed the outcomes possible in teaching situations (1982, p.630):

- Sometimes there was a 'unified scientific outcome', where the learned meanings closely matched that intended (pp.630-1).
- More often there would be a *two perspectives outcome* (§2.3.5), where the preexisting conceptions and the newly learnt material would co-exist (p.624).
- Sometimes CHILDREN'S SCIENCE would be largely undisturbed by 'teaching' (Pope and Gilbert, 1983, p.201).
- There could even be a *reinforced outcome* (§2.3.6) where the material presented is (mis)understood to support the learner's existing ideas.
- Sometimes there would be *partial learning* of ideas (§2.3.7), as only so much new material could be learnt at one time (c.f. §1.8), so that ideas would not be fully integrated in cognitive structure, and could be contradictory.

Some of these possibilities are worth further comment:

§2.3.5: The *two perspectives* outcome.

Gilbert and coworkers reported that often there would be a *two perspectives outcome*, which they described as where "the learned amalgam of CHILDREN'S SCIENCE and TEACHER'S SCIENCE can co-exist", so students could be successful in school tests whilst retaining their CHILDREN'S SCIENCE for informal use (1982, p.624). In this situation CURRICULUM SCIENCE would be effectively rejected for use as a personal model of the world (Pope and Gilbert, 1983, p.199). One might relate this to the notion of a FRAGMENTATION LEARNING IMPEDIMENT (§1.5.2) where the learner *does not recognise* that existing ideas (CHILDREN'S SCIENCE) are related to material presented in science classes.

Driver and Erickson (1983) suggested that that whereas scientists have to closely relate their formal conceptual knowledge to their experiences of the world, school children did not generally demonstrate such integration within cognitive structure (p.46). They reported that the two different domains of knowledge could be elicited by different modes of data collection.

Studies showed that learners were more likely to apply scientific principles if questions were set as formal exercises with obviously 'scientific contexts', but they tended to revert to using their alternative frameworks in novel - and particularly 'everyday' contexts (Bliss et al., 1988; Driver, 1983, p.38, p.70; Dumbrill and Birley; 1987; Viennot, 1979, 1985a, p.433). The tendency to pay heed to irrelevant contextual factors in questions can decrease with age, but even University students can change their reasoning in (scientifically) similar questions due to perceived contextual cues (Palmer, 1997).

The notion that a learner could hold distinct, and perhaps contradictory, conceptual schemes for a single topic area has led to considerable debate about the nature - and particularly the status - of CHILDREN'S SCIENCE. Some workers have argued that children's alternative ideas do not have the form of conceptual frameworks (§2.5, §2.6), or that their ideas make up part of a system of knowledge that can not be classed as 'science' (§.2.7). These criticisms of the A.C.M. are considered in detail below.

§2.3.6: The reinforced outcome.

Sometimes instruction would result in a *reinforced outcome* where the material presented is understood to support the learner's existing ideas, so that for example new terms are used to label existing ideas (Ault, Novak and Gowin, 1984, p.459). Driver has also pointed out that in practical work conceptual frameworks may "restrict empirical observations" (1983, p.65, and see p.27, p.35; c.f. Kuhn 1970 {1962), p.79) and there may be attempts to 'save the phenomenon' (Driver, 1983, p.39). In these cases the CHILDREN'S SCIENCE acts as SUBSTANTIVE LEARNING IMPEDIMENTS (§1.5.3) to the intended learning.

§2.3.7: Partial learning of presented ideas.

Sometimes instruction would result in *partial learning* of ideas. As de Bono (1969) has pointed out the human brain is generally not very efficient at accurate precise recall, but rather excels at processing data in the light of existing cognitive structure (p.22). Where existing cognitive structure acts as a SUBSTANTIVE LEARNING IMPEDIMENT (§1.5.3) then although changes in cognitive structure would take place, the learner would reinterpret the presented CURRICULUM SCIENCE in terms of his or her CHILDREN'S SCIENCE and the 'learnt' version would be very different from that intended by the teacher (Ault, Novak and Gowin, 1984, p.459). In such a context Driver and coworkers refer to Vosniadou and Brewer's idea of *assimilatory concepts* (§2.3.10), described as "attempts on the part of children to reconcile their presuppositions... with the information they receive from the adult culture" (quoted in Driver et al., 1994b, p.87).

§2.3.8: *Children's science* and the nature of the curriculum.

Gilbert and his coworkers then proposed a range of possible outcomes when a learner possessing existing alternative ideas about a topic was presented with formal instruction. Driver and Erickson (1983) thought that the actual outcome was likely to vary with the nature of the taught material, so that stable alternative frameworks were more likely to interfere with learning of topics where learners will have rich early experiences (such as heat, mechanics, light) (p.49). Chemical bonding would not be considered such a topic (c.f. §1.3.2). (In terms of the notion of learning impediments used in chapter 1, we might expect teaching about chemical bonding to be impeded less by ONTOLOGICAL LEARNING IMPEDIMENTS than teaching about topics such as mechanics.) Any alternative conceptions about chemical bonding might therefore be *expected* to be relatively labile. However, Driver and Erickson recognised that even in such curriculum areas not closely related to everyday experience a learner was likely to draw analogies with existing knowledge to make sense of the topic area (p.49, c.f. §2.8.4).

§2.3.9: The status of *children's science*: barriers or bridges?

The lack of understanding about how conceptual development occurs (see §2.10) has resulted in uncertainty over how learner's alternative ideas should be considered. Researchers who see children's alternative ideas in science in terms of misconceptions would view these ideas as *barriers* to 'correct' learning. The A.C.M. have taken an alternative view: that as CHILDREN'S SCIENCE is the starting point from which further learning must occur, it is appropriate to consider children's science as 'bridges' or 'stepping stones' on the 'path' to the intended understandings of CURRICULUM SCIENCE.

The constructivist writers recommended that teachers should develop diagnostic skills to identify CHILDREN'S SCIENCE, (Watts et al., 1982, p.3, p.27). They presented a vision of science teaching as ***building on*** the foundations of children's ideas, and developing and extending their thinking towards the scientific models (Driver, 1983, p.3; Gilbert et al., 1982, p.631; Watts et al., 1982, p.7, p.27), and they have emphasised the potential links between CHILDREN'S SCIENCE and CURRICULUM SCIENCE (Ault, et al., 1984, p.459). More recently, the influence of the Vygotskyan perspective (see §2.4.2) may be detected in the work of writers who see learning as a sociocultural process of bridge-building between informal and formal knowledge systems (Driver et al., 1994b, p.94; Hennessy, 1993, p.7).

In emphasising the importance of CHILDREN'S SCIENCE the constructivists provided ammunition for critics such as Matthews (1993) to accuse them of being 'relativists' (c.f. §2.0). Examples include:

- teachers should not think of "a matter of ***not understanding*** but of ***understanding differently*** from what was intended" (Nussbaum and Novick, 1982, p.184);
- it was necessary "to explore and empathise with children's frameworks" (Watts, et al., 1982, p.27), because they had "both important epistemological value and high educational status" (p.7);
- learners' ideas are "personally ***viable constructive alternatives*** - rather than the result of some cognitive deficiency, inadequate learning, 'carelessness' or poor teaching" (Gilbert and Watts, 1983, p.67);
- alternative frameworks uncovered in Watts' research were described as "***coherent, internally logical*** conceptual frameworks based upon [pupils'] own experiences which are *very successful* in explaining everyday events", and it was suggested that they should be given "due status" (Pope and Gilbert, 1983, p.198) as they were not only "plausible" but also "*fruitful*" for the pupils (p.199);
- learners' alternative frameworks were "in keeping with their experience and in this respect ... ***not 'wrong'*** ... perhaps just not as inclusive as the accepted 'scientific' view" (Driver, 1983, pp.87-88).

Although these workers were right to emphasise the pedagogic importance of children's ideas in science, it could be argued that in view of the traditional philosophical outlook of many school teachers (see §2.0), with a realist notion of knowledge (Pope and Gilbert, 1983, p.193; Tobin, 1990, p.34) such 'relativist' statements might have deterred some educators from taking up their ideas. Writing that was intended to 'sell' the constructivist position may have failed to take the existing conceptions of an important part of the audience - classroom practitioners - into account.

§2.3.10: Stepping stones between *children's science* and *curriculum science*.

According to Driver, the building of bridges between CHILDREN'S SCIENCE and CURRICULUM SCIENCE may involve 'intermediate notions' or 'intermediate conceptions' (Driver, 1989, p.483; Driver et al, 1994b, p.81), so that progression may follow *conceptual trajectories*, defined as "a sequence of conceptualizations which portray significant steps in the way knowledge within the domain is represented" (Driver et al., 1994b, pp.85).

Driver suggested that one part of the learning process should involve learners' theories being made explicit so that they could be compared and challenged (1983, p.76), and this was indeed a key part of the teaching schemes developed by her CLiSP research group (Brook and Driver, 1986; Wightman et al., 1986). Pope and

Gilbert also suggested that learners should be encouraged to reflect on their ideas, and thought that their role as constructors of theory should be explicit (1983, p.193). Ault, Novak and Gowin suggested that learners should learn to spot the 'tangles' and 'twists' in their own conceptual schemes (1984, p.460). Unfortunately more recent research into children's ideas about the *nature of science* suggests that although they do use models, they often do not generally have the metacognitive awareness to conceptualise their thinking in this way (Driver, et al., 1996, p.139, Duveen et al., 1993, p.25).

§2.3.11: The value of having alternative conceptions.

Ault, Novak and Gowin (1984) studied learner's notions of the 'molecule' concept using a method for interpreting and representing data collected through clinical interviews (p.441). As they investigated the same individuals on two occasions (in second grade, and then in seventh grade) they were able to draw some conclusions about the development of conceptual understanding. They found that it was better for a young pupil to have a variety of alternative conceptions than few conceptions at all, as understanding evolved more rapidly from a rich conceptualisation. If a pupil in an early grade held a range of idiosyncratic meanings these would tend to persist, but still provided a better structure for conceptual development, than a poor range of notions (p.459-60).

Hennessy (1993) points out that while some alternative conceptions are best considered as the foundations for building conventional notions, others might be of value in themselves, as the alternative models may be more appropriate in some contexts (p.9). Whilst this may seen to reflect the relativist statements criticised above (§2.3.9), this is certainly a view which could have some value in chemistry with its manifold models (§1.7.1). The 'situated cognition' perspective is considered further below (§2.7.2).

§2.4: The units of analysis of *children's science*.

In 1988 Abimbola made the seemingly obvious point that "it is important that science education researchers understand themselves when they use terms that describe student conceptions in science" (p.175). The platitude was appropriate in view of lack of consistency of the nomenclature being used in the field. In 1983 the constructivist movement in science education had been described as being in a pre-paradigmatic phase (Gilbert and Watts, 1983, p.61), and in particular it was noted that there was little agreement over the terms used to describe aspects of learners ideas elicited during research (Driver and Erickson, 1983, p.46; Gilbert and Watts, 1983, p.69). The use of term 'frameworks' was especially unclear, and although there were attempts to clarify it, these did not succeed (Black and Lucas, 1993, p.xii).

Gilbert and Watts highlighted the need to distinguish between "an individual's psychological, personal, knowledge structure" (pp.45-65) - e.g. the 'concept' as inferred to be in the learner's head - and aspects of "the organisation of public knowledge systems", i.e. the orthodox academic version of the 'concept' as presented in the textbooks etc. Phillips has criticised the error of confusing these two distinct phenomena, "disciplinary structure and cognitive structure", in the work of Piaget (Phillips, 1987, p.139).

I would suggest that there are a number of other distinctions that need to be kept in mind when talking about learners ideas:

1) between an individual's cognitive structure (which can only be conjectured, §1.4.1), and researcher's own models (which can be formally represented in words and diagrams);
2) between representations of aspects of an *individual's* cognitive structure, and general models which are intended to reflect *commonalities* from the representations derived from several individuals;
3) at different scales within an individual's cognitive structure.

The first of these distinctions closely parallels the distinction that Gilbert and Watts, and Phillips, have emphasised, but where the disciplinary structure of interest is that of constructivism itself. Ault, Novak and Gowin (1984) are careful to distinguish cognitive structure from the representation that is a product of their analysis. They use research data to infer a '*conceptual structure*' that they consider "a best approximation of cognitive structure, the 'true object' of interest" (1984, p.446), but this terminology has not been widely taken up. Lakoff and Johnson describe the difference between our cognitive structures and our public representations of these structures as a "most important distinction" (1980, p.206).

§2.4.1: The meaning of the term alternative frameworks

All three distinctions are confused in the various uses of the word 'framework'. Driver clearly used the terms 'conceptual framework' and 'alternative framework' to refer to aspects of an ***individual*** learner's cognitive structure, that is for "the mental organisation imposed by an individual" (Driver and Erickson, 1983, p.39) which was utilised "for conceptualising their experience of the physical world" (Driver and Easley, 1978, p.62).

In contrast the Surrey group used the same term to refer to their representations of *commonalities* in their *models* of aspects of the cognitive structures of many individuals, so that a framework may be described as "a composite picture based upon *ideas shared by a number of pupils*" (Watts, Gilbert and Pope, 1982, p.15, my emphasis), "generalised non-individual descriptions" and "thematic interpretations of data, stylised, mild caricatures of the responses made by students" (Gilbert and Watts, 1983, p.69).

To summarise this difference, for Driver, the conceptual framework is part of an individual's cognitive structure, something *inside the mind of a learner*, where for Gilbert and Watts the 'framework' is something presented in the public domain that is *constructed by the researcher* on the basis of data collected from a selection of learners.

Gilbert and Watts suggested that the term 'conceptions' "be used to focus on the personalised theorising and hypothesising of individuals" (1983, p.69), although in places they appeared to use the word 'framework' when by their own definitions they meant 'conceptions' (Gilbert and Watts, 1983, p.83, p.86; Watts, 1982, p.116; 1983a, p.217; Watts and Gilbert, 1983, p.168-9). Gilbert and Zylbersztajn (1985) refer to alternative conceptions as "alternative views of the world" and "personal explanations, which make sense from an individual's point of view". They suggest conceptions may take "the form of expectations, beliefs and meanings for words" (p.107). In practice the term 'conception' seems to have sometimes been used synonymously with 'framework', as when Watts and Gilbert report that "eight conceptions [sic] of the word *force* have been identified ... and seven conceptions [sic] for *energy*" (Watts and Gilbert, 1983, pp.161). Hewson actually notes that in her writing "alternative frameworks are referred to as alternative conceptions" (1985, p.154).

One source of confusion is when an author makes references to *students using* *frameworks*. This seems to have two distinct meanings. Firstly learners are said to use their frameworks when perceived regularities in their answers to questions *suggest* a coherence and logic to their thinking processes, which leads to the *hypothesis* that the topic being explored is represented in some form in cognitive structure. In other words we are talking about something which is inherent in the learner, and exists before the researcher sets about interpreting data.

At other times the statement that learners use frameworks appears to mean something very different: that once the researcher had set up a model consisting of a set of representations of possible alternative meanings for the focal topic, it was then possible to support the authenticity of the analysis by demonstrating the compatibility of representations with extracts of interview transcript.

§2.4.2: Alternative frameworks may be ubiquitous or elusive: the danger of 'framework spotting'.

This distinction is important because although constructivism has been considered a dominant paradigm in science education research (Solomon, 1994, p.7), it does not have universal acceptance amongst active researchers in science education (e.g. Kuiper, 1994). Indeed it is probably more helpful to think of Lakatos' notion of research programmes here (1970 {1965}).

The research reports of the constructivists (such as Watts 1982, 1983a, 1983b) could be argued to be based around two claims:

- claim 1: learners have 'ALTERNATIVE FRAMEWORKS 1'.
- claim 2: Watts and others have constructed some 'ALTERNATIVE FRAMEWORKS 2'.

where the subscripts refer to two discrete meanings of the term framework: ALTERNATIVE FRAMEWORKS 1 are "the mental organisation imposed by an individual on sensory inputs" (Driver and Erickson, 1983, p.39), and ALTERNATIVE FRAMEWORKS 2 are "thematic interpretations of data, stylised, mild caricatures of the responses" (Gilbert and Watts, 1983). For a worker within the *paradigm* (Kuhn) - participating in the same *research programme* (Lakatos) - these two knowledge claims have a very different status.

Claim 1 is a reference to one of the key aspects of the *disciplinary matrix* (Kuhn). In Lakatos' terms it is part of the *hard core* of the *research programme*: something that is protected by the *negative heuristic*, i.e. workers within the *research programme* will not find it fruitful to undertake research to falsify the claim, which is an essential prerequisite for the *programme* to proceed. Claim 1 is a claim about the tenets of constructivism.

Claim 2 concerns only the proficiency of the researcher as a competent practitioner in the field. The *positive heuristic* of the *research programme* leads to enquiry into eliciting learner's ideas, and constructing representations which (a) other researchers accept as authentic, and (b) are in a form which may be readily communicated to those teaching science. Individual examples of claim 2 make up part of the *protective belt* of theory in the *research programme*.

For researchers in the constructivist tradition claim 1 is therefore axiomatic, whereas specific examples of claim 2 are peripheral. A statement that ALTERNATIVE FRAMEWORKS 1 do not exist is an attack on constructivism, and by definition can not be made from *within* the *research programme*. A statement that certain ALTERNATIVE FRAMEWORKS 2 do not exist is merely questioning the work of one individual researcher, and does not necessarily have serious implications for the *research programme*. Indeed criticisms of ALTERNATIVE FRAMEWORKS 2 would be quite proper within the *programme*, and such debate would indeed be directed by the *positive heuristic*. It is analogous to the difference between denying the existence of fairies at the bottom of the garden, and arguing over what their names are. (Or the difference between denying that continental drift takes place, and disagreeing over the precise rate at which the Atlantic is spreading.)

Having established this distinction it is now appropriate to consider an example of criticism of constructivist research - on the theme that alternative frameworks do not actually exist. In 1983(a) Watts published results of his research into student understanding of the concept of force, summarising his findings in terms of eight alternative frameworks. Eleven years later Kuiper (1994) questions the use by some science education researchers of the assignation "alternative frameworks" to aspects of student thinking revealed during enquiry. In Kuiper's own study of student ideas about force he not only failed to support the specific findings of Watts and others, but made a claim that:

- "students in general do not have an 'alternative framework' for force" (p.279).

This discrepancy requires some comment. However a reading of the meanings these two authors give to the term 'framework' is enlightening. Kuiper comments that,

> "The use of the term framework in the description of student understanding implies an ordered and schematic understanding of a concept. This term can be understood to mean that a *particular student* has a set of student ideas concerning one and the same concept which *appear to be* logically coherent and ordered."
> (Kuiper, 1994, p.280, my emphasis.)

There are two important points that need be raised from this extract. The first relates to the basic tenets of constructivism on which much of this field of research is 'built'. According to P.C.T. (Kelly, 1963, see §2.2.4) the learner and the researcher have different construct systems, and that what is "logically coherent and ordered" in terms of the learner's construct system, may well *appear to be* confused and contradictory when re-interpreted through the researcher's own construct system. The research process may be understood in terms of the researcher developing his or her construct system to try and see things the way the learner does. Kelly refers to "the credulous attitude" (1962, p.174), and the metaphor of putting on different goggles has been used (Pope and Watts, 1988). Kuiper used a test where "the same problem was put four times, only placed in different contexts" (p.281). The assumption being that "if students are to have alternative frameworks, then certainly the same problem, in different contexts, should be answered with the same student idea" (p.281). However it could be argued that what was the same problem for the researcher was several different problems when viewed through the construct system of the learner. As Edwards and Mercer point out, *context* "is essentially a mental phenomenon", and "participants' conceptions of each other's mental contexts may be wrong or, more likely, only partially right" (1987, pp.160-161).

So there is the danger of a tautological argument here. The argument could be summarised as *what is 'alternative' does not appear consistent and therefore cannot be a 'framework', whilst that which qualifies as a 'framework' must seem logical within the researcher's own construct system, and is therefore not considered 'alternative'*. 'Alternative frameworks' therefore become a logical impossibility within the perspective in which the research is conducted. The discussion also ignores (or perhaps excludes) what have been termed 'multiple frameworks' (discussed below, §2.5.2).

The second point of importance here is that Kuiper is referring to individual conceptual frameworks, or ALTERNATIVE FRAMEWORKS 1, whereas Watts' research was reporting ALTERNATIVE FRAMEWORKS 2 - "a simplified description" that came "from no *one* pupil", but had "been pieced together from the implicit and explicit conceptions used by the children" to "form a composite picture based on the ideas shared by a number of pupils" (1983a, p.218).

These two workers were also using different techniques to collect data. Watts was working with interviews, an approach that allows considerable interaction between the discussants (see for example Powney and Watts, 1987) and has been found particularly useful for eliciting learners' conceptions (§4.6); whereas Kuiper used written test items which do not provide the flexibility of the 'conversational' approach fundamental to constructivist enquiry. Whereas Watts was working within the 'interpretive' research paradigm (i.e. 'paradigm 2' in terms of Gilbert and Watts (1983), see §4.1), Kuiper's paper is clearly based on a very different - i.e.

normative - approach ('paradigm 1' according to Gilbert and Watts), using the written responses classed against a small number of *predetermined* categories.

Pope and Denicolo (1986) had foreseen the dangers of 'frameworks' in the naturalistic research literature being taken out of context by those working in a reductionist manner. They explained that authentic reports would describe the subtleties of individual learners' ideas, and the stages of data reduction used in the analysis. However such reports would be too detailed and dense to be read by the teachers to whom they were addressed, and too long to be published in most journals. Thus "authenticity must be tempered with utility" (p.156). Pope and Denicolo used Watts' work as an example: as he had "clearly described his data degradation process as he moved from consideration of [the] child's alternative conceptions, through categorisation of exemplars of these conceptions using verbatim quotes as evidence to the production of descriptions of a range of *alternative conceptual frameworks*" (p.157). They warned against ignoring this analytical process ("although starting from a holistic approach *one* 'end product' of his work is a much reduced description of the construing of the individuals in his study which, if taken out of context, is also devoid of consideration of the particular choices made by the researcher in his conduct of data collection and analysis", p.157), and suggested that,

> "the busy teacher or researcher with a predilection towards reductionism may well ignore the 'health warnings' conveyed in our research report. Instead they will indulge in a 'framework spotting' exercise using reified descriptions of frameworks and ignoring the ontology of these frameworks."
> (Pope and Denicolo, 1986, p.157.)

Kuiper's study suggests that he has indeed ignored Watts' 'health warnings', and - at least in part - this is the error of reading reports of ALTERNATIVE FRAMEWORKS2, and assuming they refer to ALTERNATIVE FRAMEWORKS 1.

§2.4.3: Alternative frameworks and alternative conceptions.

With regard to the third distinction in my list, Driver included in the term alternative frameworks both "an idiosyncratic response to a particular task" and "general notions applied to a range of situations" (1983, p.7). I would argue that it is useful to draw a distinction between aspects of cognitive structure which influence student behaviour (such as answers to questions) in response to a range of stimuli (such as a series of questions on a topic area), and the level of thinking that produces a single proposition. It has been suggested that "propositions are the 'molecules' from which meaning is built and concepts are the 'atoms' of meaning, to use a rough metaphor" (Novak, 1985, p.192). The identification of *conception* with proposition seems to reflect workers such as Hewson for whom "the term conception is used to indicate a functional unit of thought" (1985, p.154), and

Strike and Posner who "make no distinction between *conceptions* and *ideas* and use the terms interchangeably" (Strike and Posner, 1985, p.213, italics in original).

The term framework suggests 'a basic structure which supports and gives shape' (Longman Modern English Dictionary, Watson, 1968) and Abimbola uses *framework* in such a sense, as "the *organization of ideas* rather than the ideas themselves", so that "*alternative frameworks* are just the undergirders that anchor ideas" (1988, p.181). This is consistent with Ault and coworkers' notion of conceptual structures, models of aspects of cognitive structure "likely to *generate*" a student's "claims about events" (Ault et al., 1984, p.446, my emphasis), and to Viennot's approach to investigating within which framework elicited student conceptions occur (Viennot, 1985a, p.433).

§2.4.4: Alternative frameworks and gestalts.

The two terms considered above, *conceptions* and *frameworks*, are very commonly used in the literature. The term *gestalt* is much less common, but may also be useful in explaining learners' ideas in science. A gestalt is an integrated whole, and this idea forms the basis of a school of psychology (e.g. Pearls et al.,1973 {1951}) that is based on the premise that "mental processes and behaviour cannot be analysed, without remainder, into elementary units, since wholeness and organisation are features of such processes from the start" (Drever, 1964 {1952}, p.108).

Lakoff and Johnson (1980) have argued that the human conceptual system largely functions through metaphor containing metaphorical as well as nonmetaphorical concepts (p.195). They define *nonmetaphorical* concepts as "those that emerge directly from our experience and are defined in their own terms, [such as] ... spatial orientations ... ontological concepts ... structured experiences and activities" (p.195). *Metaphorical* concepts "are those which are understood and structured not merely on their own terms, but rather in terms of *a different kind* of object or experience" (p.195, italics in original). They describe the metaphorical structure as "extremely rich and complex" (p.195).

These authors claim that metaphorical concepts are grounded in experience (p.204) and are "based on complex experiential gestalts" (p.201), by which they mean "a multidimensional structured whole arising naturally within experience" (p.202). A particular experiential gestalt is described as being either

- "a structure within a person's experience that identifies that experience as being of a certain kind", or
- "a structure in terms of which a person understands some external occurrence and that identifies that occurrence as being of a certain

kind" (p.205).

Like *frameworks*, *gestalts* may be understood as reflecting an aspect of cognitive structure which is used to interpret perceptions and organise thoughts. However whereas *frameworks* may be considered to reflect aspects of cognitive structure that are to a large extent consciously available to the learner - so that it would be possible to sit down and discuss an individual *framework* with the learner in terms of the propositions from which it is constructed, and to authenticate the *framework* in a piecemeal manner - the *gestalt* may be envisaged as reflecting an aspect of cognitive structure which is a fundamental aspect the individual's world view, but which is largely tacit.

Perhaps such *gestalts* (or rather the cognitive structures that lead to their perception) are not unlike Piaget's "system of mental tendencies and predilections of which the child himself has never been consciously aware and of which he never speaks" (1973 {1929}, p.14), and are akin to Vygotsky's spontaneous concepts that "the child becomes conscious of ... relatively late" (1986 {1934}, p.192, §2.2.2). Vygotsky discusses the process whereby "scientific concepts ... supply structures for the upward development of the child's spontaneous concepts towards consciousness and deliberate use" (p.194). As the structures which lead to the perceptions of gestalts do not concern classes of objects, but broad basic assumptions about the way the world is, it might be expected that the process of bringing them to conscious and deliberate use is more complex than that envisaged by Vygotsky.

Polanyi (1962 {1958}) has described what he calls the *ineffable* domain, as "where the tacit predominates to the extent that articulation is virtually impossible" (p.87), and has pointed out that this domain can not be examined by introspection,

> "The curious thing is that we have no clear knowledge of what our suppositions are and when we try to formulate them they appear quite unconvincing."
> (Polanyi, 1962 {1958}, p.59.)

The distinction between frameworks and gestalts may be useful even if it does not represent an *absolute* division in cognitive structure. Because the proclivities leading to gestalts concern fundamental ways of organising experience of the world they can influence thinking over a wider range of phenomena and situations than the framework; and because that are largely tacit, they are more difficult to investigate than 'conceptions' or 'frameworks'. The research literature includes a multitude of alternative conceptions, a range of alternative frameworks, but only a few papers claiming to have uncovered gestalts.

Anderson (1986) proposed that one of Lakoff and Johnson's gestalts, the 'experiential gestalt of causation' was of particular significance: "a common core to ... pupils' explanations and predictions in such widely differing areas as temperature and heat, electricity, optics and mechanics" (p.155). This gestalt concerned causality, and the suggestion was that many disparate phenomena were perceived in terms of an *object* that is acted upon by an *agent* through the use of an *instrument*. The suggestion was that where conventional science teaching concerned phenomena that were *not* presented in these terms, misunderstanding could commonly occur. For example, in the case of inertia (i.e. Newton's first law of motion, §3.1.3): "the idea of motion with no force whatsoever goes absolutely against the experiential gestalt of causation, that successful organizer of so much experience" (p.169). The tacit nature of the gestalt may be understood in terms of it developing in the very young mind before the acquisition of language.

Watts and I have suggested that data from learners in a similarly wide range of science topics supports the existence of another gestalt that forms the basis for deciding which phenomena need to be explained in analytical terms, and which are accepted as just being. This *explanatory gestalt of essence* (Watts and Taber, 1997) is proposed to explain why it is that learners are often prepared to give reasons - sometimes quite creative *ad hoc* reasons - to explain many phenomena, but for others seem nonplused by the question and can only respond in terms of "it's natural". This response seems unlikely to mean just 'I don't know and I can't think of any suggestions' when the same individuals show fertile imaginations in response to different questions. It seems that learners genuinely construct explanations for phenomena that are recognised as justifying them - both spontaneously and when provoked by educational researchers - but reach what *for them* are 'first principles' where the idea of further explanation becomes non-sensible.

Again it seems likely that this gestalt has its origins in early life experiences, so that the learner is not consciously aware that he or she reaches a point where explanation comes to a stop, and so when these 'first principles' are questioned it is not just that the learner *can not* answer the question, but rather that he or she perceives the question as meaningless within his or her world view (akin to the cosmologist frustrated by the question "if time and space were created in a 'big bang', then what existed *before* this?")

The *experiential gestalt of causality* is proposed as a representation of something universal in human cognitive structure. Similarly, the *explanatory gestalt of essence* seems to be widespread: learners generally appreciate the function of explanation - but often seem to reach the "it just is" point.

§2.4.5: Phenomenological primitives.

The notion of *phenomenological primitives*, or *p-prims*, may be considered a similar idea to that of *gestalts*. Hammer (1996) describes how diSessa's *p-prims* are considered to be stable aspects of cognitive structure, which make up one's intuitive physics. These primitives are small units, such as *closer means stronger* (p.7) which are potentially widely applicable. From this perspective many alternative conceptions elicited from students are not in themselves necessarily stable, but are constructed in situ using one of the *p-prims* held in cognitive structure (so once a 'closer means stronger' *p-prim* is developed it might be applied in a wide range of contexts such as loudness, intensity of light, and so on).

§2.5: Criticisms of the notion of alternative frameworks.

> "One open question is the extent to which children's conceptions are genuinely 'theory-like', that is having a coherent internal structure and being used consistently in different contexts..."
> (Driver, 1989, p.483.)

The constructivist position outlined so far might be summarised that

1. learners, especially children, come to science classes with their own explanations of scientific phenomena, and that
2. this CHILDREN'S SCIENCE *may* interfere with the intended learning.

This position has been widely debated and point 1 is generally accepted. However there has been considerable debate over ***the nature*** of such CHILDREN'S SCIENCE Kuiper's criticisms of the the idea of alternative frameworks have been considered above (2.4.2), but other workers have suggested that the A.C.M. may be over-emphasising the extent to which CHILDREN'S SCIENCE acts as a competitor to CURRICULUM SCIENCE (§§2.5-2.7).

In particular there have been discussions on

1. the extent to which learners alternative ideas are *stable*, rather than being largely created in the context of clinical interviews, test situations or social chit-chat;
2. the extent to which CHILDREN'S SCIENCE is theory-like, in terms of having the coherence expected of scientific explanatory frameworks;
3. the extent to which CHILDREN'S SCIENCE comprises of ideas which are integrated together in cognitive structure, rather than being a

collection of discrete conceptions.

These debates are very important for the present thesis. If learners hold alternative conceptual frameworks for science concepts which are stable over long periods of time, which are coherent and self-consistent, and which are closely integrated with other concepts represented in cognitive structure, then these might be expected to make up significant SUBSTANTIVE LEARNING IMPEDIMENTS (see §.1.5.3). If this is the case then the study of such conceptual frameworks might produce much of pedagogic value. Part of the ***raison d'être*** for research into learners' alternative conceptions and frameworks is the claim that they can be extremely tenacious and difficult to extinguish (e.g. Driver et al. 1985b) and therefore teachers need to be aware of their existence.

However, if it were to transpire that CHILDREN'S SCIENCE is a labile collection of incoherent and self-contradictory notions, ***largely generated through the process of elicitation itself***, then it would not be expected to act as SUBSTANTIVE LEARNING IMPEDIMENTS. (Indeed, as Solomon has pointed out, activities designed to ***elicit*** alternative conceptions may catalyse their ***generation***, see §2.8.3). If this were the case then learning difficulties would have to be sought elsewhere (for example as NULL LEARNING IMPEDIMENTS, see §1.5.3).

In practice, a wide range of positions have been taken by workers in the field, all supposedly based on empirical data collected from learners.

§2.5.1: Stability of *children's science*.

In 1983 Driver reported that research indicated that alternative frameworks did not seen to be extinguished by teaching (p.76). Driver explained that where learners were presented with material at odds with their cognitive structures they had to both understand the new ideas, and to be prepared to move outside of their existing modes of thinking - "to make the intellectual leap of possibly abandoning an alternative framework which until that time had worked well for them" (p.9, see also p.41). Therefore the time-scale over which substantial learning could be expected to occur would be long term, i.e. months and years (Driver and Erickson, 1983, p.54). From a Vygotskian perspective (§2.2.2) "learning science should involve the gradual integration of personal experience and knowledge into the complex systems of models and theories, and the ways of thinking, that scientists use to explain natural phenomena ... children need time to get used to and accept new ideas and other ways of understanding phenomena ... and ... time to move back and forth between everyday concepts and scientific concepts" (Howe, 1996, pp.47-48). As Hennessy points out scientists become experts through a long process of cognitive apprenticeship, where they spend years acquiring both ***intuitive*** knowledge and "sophisticated mental models" of their specialist field (Hennessy, 1993, p.1). (Models of how such change occurs are discussed later in this chapter, §2.10.3. A basic assumption of these models is that conceptual change may be a rational process, which ignores the possibility that learners have have emotional commitment to their existing ideas - particularly where they have acquired them from a significant other such as a parent, close friend or favourite teacher).

Aware that much of the research data available had been collected from individuals on one occasion, Gilbert and Watts suggested the need for "successive re-inquiries" into the frameworks used by individuals over several years (p.87). The present research has such a longitudinal nature (§1.8, and in particular see the case studies in chapters 7 and 8).

Some critics have claimed that there is evidence from many learners that they do *not* have *stable* alternative conceptual *frameworks* at all, but that their informal knowledge is changing all the time. Solomon (see below, §2.7) has discussed Pine's doctoral research into young children's ideas in a range of science topics which suggested that children's notions changed over time as well as being multifaceted and dependent upon context (1992, p.28). She has also pointed out how research into various topics had demonstrated how children seemed to quite readily move between applying different alternative frameworks, even in a single interview (p.24). Other authors (such as Claxton, see below, §2.6) have suggested that student thinking about a topic often seems not so much to reflect a conceptual 'framework' as a wide set of distinct ideas that are applied locally, according to the perceived context. Although workers such as Solomon and Claxton draw attention to an important feature of learners' thinking, it will be argued in this thesis that their criticisms of the notions of stable frameworks are misguided. Firstly it is important to distinguish stability from coherence. This distinction is recognised in Kelly's P.C.T. (§2.4.4) in terms of his 'fragmentation corollary', that is, that "a person may successively employ a variety of construction subsystems which are inferentially incompatible with each other" (1963 (1955), p.83). From a Kellyan perspective, an individual could have a stable construct *system*, yet give the impression of flitting from one notion to another. The case for learners' alternative ideas being *stable* does not require learners to have conceptual frameworks which satisfy the criteria applied to public science (in terms of logical coherence). Driver et al. have emphasised the distinction,

> "It is often noticed that even after being taught, students have not modified their ideas in spite of attempts by a teacher to challenge them by offering counter-evidence. ... Although students' notions may be persistent, as we have already argued, this does not mean the student has a completely coherent model of the phenomena presented. The students' interpretations and conceptions are often contradictory, but none the less stable."
> (Driver et al., 1985b, pp.3-4.)

The phenomena of 'multiple frameworks' will be discussed further below in the next subsection (§2.5.2). It should also be pointed out that those researchers who argue that alternative conceptions and frameworks are 'stable' do not consider them to be totallyimmutable, or there would be little purpose in advising teachers how to bring about conceptual change (§2.10.5).

§2.5.2: The coherence of *children's science* - multiple frameworks.

Some workers have claimed then that children can hold alternative frameworks about scientific topics which are stable, theory-like, and may be consistently applied. However, research into learners' alternative frameworks in different areas of the science curriculum has *suggested* that the same individual often exhibits evidence of holding to more than one alternative framework for a particular science concept.

Pope and Denicolo (1986) have observed that where researchers had presented a range of alternative frameworks to describe learners ideas on a topic, the data may suggest that some learners exhibited *multiple frameworks*, that is "where, within one utterance or short speech act, more than one of [the proposed] frameworks was projected" (p.158). Pope and Denicolo suggested that although it would often be *possible* to artificially 'disaggregate' a learner's statements into smaller parts which could independently be fitted to the different frameworks, such a process was not an authentic representation of utterances that seemed to genuinely encompass several categories that the analyst considers distinct (p.159) .This raises the question as to whether the learner holds *multiple frameworks* for a topic, or a single coherent framework which does not fit the categories in the researcher's model (which is an abstracted and simplified set of alternative frameworks, see §2.4.2). For as Viennot has pointed out, the very things that make an individual's thinking 'alternative' make it difficult to comprehend, and describe, as the learner may use different terminology, and her alternative notions do not necessarily match the concepts of science through a "one-to-one correspondence" (1985a, p.433. See also my earlier comments about Kuiper's criticisms of alternative frameworks, §2.4.2). The tendency is for the learner's comments to be interpreted through the construct system of the researcher, that is to try and make sense of the learner's utterances in terms of CURRICULUM SCIENCE (p.433). It would certainly seem *feasible* that in some cases researchers may have failed to fully appreciated learners' unified alternative frameworks and misidentified utterances as representing several discrete frameworks.

Indeed it might be asked how a researcher could ever understand a learner's thinking if their construct systems were so different. Followers of Kelly might refer to his adoption of the *credulous attitude* (1963 {1955}, p.174) - perhaps this could be crudely paraphrased that nothing should be ruled out in advance. For Kelly, understanding another person requires the researcher to "subsume the constructs of the subject" (p.174). From the perspective of P.C.T. the researcher has to develop his or her construct system to include new constructs that model the construct system of the learner (see §2.4.4 above), and Kelly warns against "ignoring the personal construction of the [researcher] who does the observing" (p.174).

It is a tacit assumption in the field that - for example - a researcher could acquire a new notion of force, that is inconsistent with his or her own understanding, but which stands for a learner's apparent understanding - and that the researcher can do this without having to give up his or her own alternative (in the literal sense) notion. 'My understanding of learner X's concept of force' may be stored in cognitive structure without significantly interfering with 'my understanding of force'. In a similar way, a historian of science would be able to hold a range of 'versions' of the force concept, which could be labelled 'my understanding of Aristotle's notion of force', '...Galileo's notion...', '...Newton's notion...', and so forth.

It would be generally accepted therefore that an individual could hold 'multiple frameworks' for 'a concept', where these frameworks were ***understood by the individual*** to refer to distinct 'versions' of the concept, and therefore actually ***different*** concepts. In other words, where the construer has reason to construe distinct versions of a concept, we would expect to be able to infer 'multiple frameworks' within the concept area. In the examples given above (the educational researcher, the historian of ideas) the distinctions between possible frameworks are clear to the conceiver and to others.

If this is accepted then it seems reasonable to suggest that there may be occasions when *a learner* may perceive (consciously or otherwise) a distinction that justifies applying different frameworks, although *the observer* may not initially appreciate the distinction. There are reports in the literature that learners may compartmentalise learning in ways that teachers do not intend. For example a learner may effectively master the scientific version of a concept, and apply it in the context of classroom and examination questions, but chose to answer questions in an 'everyday' setting according to an alternative set of ideas (see §2.3.5 above). The learner distinguishes 'life-world' and 'school' knowledge in a way that the teacher does not. (The term 'life-world' is that used by Solomon, as discussed below, §2.7.1). If the learner has to be able to converse with peers and parents in out of school contexts, it way well be more appropriate if 'life-world knowledge' is applied in such contexts, as this is how effective communication will occur. As Driver et al. comment, "human beings take part in multiple parallel communities of discourse, each with its specific practices and purposes" so "we would not expect students necessarily to abandon their common-sense ideas as a result of science instruction" (1994c, p.8).

It would seem then that when a learner seems to display 'multiple frameworks' for a topic it may be that a unified coherent conceptual scheme is not apparent to the researcher because he or she has not been able to fully construe (model) the learner's constructs system. Alternatively, there is no reason to rule out the possibility that learners do indeed hold multiple frameworks to explain some phenomena, (and that they may be triggered into applying particular frameworks by particular cue or mind sets). This idea is developed in the section on conceptual change (§2.10).

§2.6: Claxton's alternative perspective: minitheories.

Claxton (1993) has been one critic who has suggested that it is naïve (a "gross simplification") to infer that learners have alternative frameworks based on the utterances collected during research (p.45). Rather, Claxton points out, such utterances may be reflections of specific circumstances ("an unprecedented question ... a unique nexus of opportunities, abilities, constraints and personal history") as much as underlying cognitive structure (p.45). He suggests that our interactions with learners allow us to access their *thinking*, but that this is a *process* of constructing ideas *in situ*, rather than a *reporting* of stable conceptual structure, that is that the researcher's construction of an 'alternative framework' may be no more than an "ephemeral reflection" of that construction process (p.45). As Ault, Novak and Gowin point out, people may indeed hold "multiple, contradictory notions" but some of these elicited in research *may* be "transitory artifacts" of the interview itself (1984, p.447).

In Claxton's view, the underlying cognitive structure itself may be better modelled as a large number of discrete 'minitheories', rather than as expansive conceptual frameworks (i.e. learners holds alternative conceptions, but not fixed alternative frameworks, c.f. §2.4.3.) According to this view, young people's ideas are fragmentary, invented ad hoc, and have limited ranges of application (1993, pp.46-47). Claxton suggests school children exhibit three categories of minitheories that he labels 'gut science', 'lay science', and 'school science' (p.50).

Claxton's *gut science*, which "stops you getting burnt and falling over" (pp.52-53), might be associated with Vygotsky's *spontaneous concepts* (§2.2.2), Pope and Denicolo's (1986) *intuitive theories* or Driver and Erickson's (1983) *theories-in-action*.

It is "acquired through experience and is expressed in unreflective, unpremeditated action" (p.52, see also §2.4.4).

Claxton's *lay science* "gives you *practical advice* about when to plant the radishes, or how to load your camera; and ... gives you intrinsically interesting things to talk about" (p.53, my emphasis). Claxton suggests that this type of knowledge does not have to be accurate, nor formalised, and it is not important "whether there is an inherent contradiction between what you are saying now and what you said yesterday" (p.53).

Claxton sees the role of *lay science* more in social terms as it "commonly comprises a store of 'amazing facts' that can be traded and discussed with others as a means of exploring or establishing friendships" (p.52), a point which has been taken further by Solomon. The notion of *lay science* has much in common with Solomon's notion of *life-world knowledge* (discussed below, §2.7.1) which she sees as "a rag-bag of odds and ends picked up from conversations of parents, teachers, and friends; from the television and magazines" from which children can select (1993b, p.88).

For Claxton (and as we will see below, for Solomon in relation to life-world knowledge), the criteria of formal science - that is "demands for rationality, logic, coherence, rigour, precision and explanation in terms of a limited set of agreed, technical concepts" - are of little importance in relation to *gut science* and *lay science* (Claxton, 1993, p.52). Collectively these two categories could be identified with CHILDREN'S SCIENCE, in the sense that they compose those views of the natural world and the meanings for scientific words held by children before formal science teaching (Gilbert et al., 1982, p.627).

By contrast Claxton's third category, *school science*, "is articulated, consciously and deliberately transmitted and received" and Claxton suggests that if it is understood it forms "a highly coherent set of ideas" (1993, p.52.) Like Gilbert et al. (§2.3.2), Claxton is careful not to suggest that 'school science' is identical to SCIENTISTS' SCIENCE (pp.50-51).

Claxton's argument - that what the A.C.M. researchers have called CHILDREN'S SCIENCE is in the form of many piecemeal, local, fragmentary minitheories - will be addressed below. However Claxton also asserts that 'school science' may be of this form. This does not seem to be consistent with his own statement that - when understood - 'school science' forms "a highly coherent set of ideas" (1983, p.52.) Perhaps Claxton means to imply that learners do not generally reach such an understanding, and so for typical school students their learning of school science does indeed make up just another cluster of minitheories. However it is harder to accommodate Claxton's suggestion that 'scientist's science' should be considered as a 'fourth cluster' of mini-theories (one of which "both school children and school teachers are largely ignorant", p.50). This suggests a radical interpretation of Claxton's ideas, that all human knowledge is stored as discrete 'minitheories' - although presumably those categorised to be in the 'scientists' science' cluster are compatible enough to give rise to coherent and logical thought when accessed in the process of thinking.

Some of the characteristics of Claxton's minitheories, the lack of apparent coherence, and the absence of application of a basic model across a range of phenomena, have been recognised by Driver (Driver et al., 1985b, p.3). However she has also pointed out that "many notions children hold are used in a range of situations and have the characteristics of elementary models or theories" (Driver and Easley, 1978, p.62). Similarly, the Surrey group referred to "conceptual structures which provide a sensible and coherent understanding of the world from the child's point of view", and which could be held "very strongly" (Gilbert et al., 1982, p.623), so that "the person resolutely holds on to the original model and rejects those of others" (Pope and Gilbert, 1983, p.201). These workers do not necessarily deny that *some* aspects of children's thinking have the characteristics of Claxton's minitheories, but they suggest that *not all* of children's ideas in science can be dismissed so readily.

§2.6.1: A synthesis of Claxton and the A.C.M.

I will treat two aspects of Claxton's ideas separately. The distinction between his different *clusters* of minitheories reflects Solomon's ideas which are discussed and criticised below (§2.7, §2.8). However the notion of minitheories itself requires some comment here.

Both Claxton and those proposing alternative frameworks (Driver, Gilbert, Watts etc.) base their interpretations on empirical data. There is no contradiction if it is accepted that: ***the alternative conceptions that make up children's science may sometimes take the form of logically connected alternative conceptual frameworks, but may also take the form of discrete and isolated knowledge fragments.***

This synthetic position may be understood in two ways:

- cognitive structure may be more integrated and coherent in some learners than others;
- in an individual learner different areas of knowledge may be represented in cognitive structure with different degrees of integration and coherence.

In the former case the overall degree of integration may be *one aspect* of intelligence (c.f. Gould, 1992 {1981}, pp.234), and *may* relate to metacognitive skills (§2.3.10, and see also §2.8.5, §2.11.3), and *may* relate to levels of maturation (e.g. c.f. Piaget's notions of development, and Vygotsky's notion of scientific concepts providing a framework for the learner to gain conscious access to spontaneous concepts, §2.2.1, §2.2.2). The empirical data that has been considered by Claxton, Driver and others has mostly been elicited from school children. However, it has derived from learners of very different ages, levels of maturity, interests and aptitudes in science.

The empirical data presented in this thesis concerns A level chemistry students, who as a group may be considered to be (a) above average intelligence, (b) relatively mature (16+ years), and (c) to have shown an interest in chemistry. These are types of the learners who might be *most* expected to hold alternative conceptual frameworks, even if much children's science is *generally* in the form of minitheories.

If the synthetic position is accepted, then a key issue for researcher in the field, is to identify the status of elicited ideas. As Driver and coworkers have suggested,

> "one of the problems involved in investigating children's ideas is devising ways of probing thinking which enables {sic} us to sort out the status of the responses we obtain; to distinguish between those ideas which play a significant part in the thinking of an individual or a group and those which are generated in an ad hoc way in response to the social pressure to produce an answer in an interview or test situation" (Driver et al., 1985c, p.196).

§2.7: Solomon's criticisms of personal construction of knowledge.

Solomon has been critical of the work of the 'alternative constructions movement', and has suggested that the notion of *the pupil as scientist* (Driver, 1983) is seriously flawed. Although Solomon's position is constructivist it is based in the social (i.e. inter-personal) rather than the (intra-)personal construction of knowledge. Her perspective therefore owes much more to Vygotskyan rather than Kellyan ideas (§2.2.2 c.f §2.2.4). By considering Solomon's ideas in some detail it will be possible to explore some of the central debates about the construction of knowledge.

§2.7.1: Solomon's two distinct systems of knowledge.

One of the outcomes of children's science interacting with formal instruction identified by Gilbert and coworkers (see above, §2.3.4) was the *two outcomes perspective* where pupils learn presented theories and explanations, and can use them in class and in tests, but revert to their existing ideas in everyday conversation and problem-solving (1982, p.624). Solomon has suggested that one should distinguish between what she labels *the natural attitude* and *symbolic universes of knowledge*. The natural attitude is characterised as to categorise experience loosely, to typify, and to absorb knowledge into fragmented meaning structures. In Solomon's scheme this leads to *life-world knowledge* which is reinforced by communication and language, and has persistence and social value. In contrast symbolic universes of knowledge (such as the theories of formal science) are fragile, have low social value, and an overarching nature. Solomon suggests that "when students learn the new formalism of scientific thought they store it in a different compartment from that of the familiar life-world thought of daily discourse" (1993b, p.96). She cites as evidence - a phenomenon she assumes familiar to teachers - learners suddenly being cued "into the domain of science knowledge" when "a whole network of meanings, theories and concepts are recollected and furnished with examples" (p.95).

According to Solomon, the domains of life-world and symbolic knowledge are dissimilar in genesis and mode of operation - and crossover involves *discontinuity of thought*. Solomon's comparison of these 'two worlds of knowledge' is presented in table 2.1.

Solomon's comparison of knowledge - in two domains

life-world knowledge	scientific knowledge
Social exchanges try to achieve a mutual understanding and agreement.	The aim of debate is to sharpen differences and to confirm or refute rival opinions.
Words used have multiple meanings which are not defined but negotiated socially.	Concept words are unambiguously defined for exact use.
Meanings are dependent on the cultural group and on the physical or affective context.	Concept meanings are symbolic and abstracted from any particular situation.
Apparent contradictions are tolerated. No logical method is thought to be needed.	A tight logical network of concepts and theories is claimed.
This knowledge system is well socialized by daily use with familiar people.	This knowledge is not well socialized since its methods are rarely used and then only by teachers outside the peer group.

Solomon, 1993b, pp.92-93.

table 2.1.

She suggests these domains of knowledge represent more than just discrete frameworks or separate clusters of minitheories, but two different *systems* of knowledge (1994, p.8). This reflects findings from mathematics education that suggest totally different strategies may be used to solve arithmetical problems in school and in 'street' contexts (Carraher et al., 1991).

From work with secondary pupils asked about energy changes, Solomon inferred that a lapse of time will select preferentially for the life-world structure of meaning if there is no further reinforcement of symbolic knowledge; and that successful crossing over and back from one domain to another will be more difficult than continuous operation in one domain, and is indicative of a deeper level of understanding (Solomon, 1992, pp.110).

2.7.2: Situated Cognition.

Solomon's distinction between life-world knowledge and symbolic universes of knowledge may be illuminated by the notion of *situated cognition*, a perspective that people have different 'ways of seeing' that are appropriate in different contexts (Driver, 1989, p.486). This is an area which has been reviewed by Hennessy (1993), who reports that both experts and lay people apply thinking that is honed in a particular problem-context (p.29). According to this view the reversion to CHILDREN'S SCIENCE (or *life-world knowledge*, or *lay science*) outside of formal learning contexts would be expected as specialist knowledge - such as formal scientific knowledge - is not considered relevant to everyday life, and does not tend to be activated in the absence of the - perceived - appropriate context (p.24).

Hennessy's review supports Solomon's emphasis on the difference in origins of *life-world* and *symbolic* universes of knowledge: the former having developed through solving problems in real-life contexts (Hennessy, 1993, p.30), whereas the latter would need to be "reconstructed" and re-contextualised before it could be used in everyday life situations (p.26). Indeed Hennessy describes schooling as "a unique culture, a specialised practice with its own conventions, organisation and concerns, which are in fact of little value to society outside" (p.2).

According to the situated cognition perspective the apparent 'partial, incoherent or internally inconsistent' nature of many alternative frameworks is to be expected as "pieces of knowledge or models are being drawn upon flexibly and according to their appropriateness and usefulness in a specific practical context" (Hennessy, 1993, pp.6-7, c.f. Claxton's ideas, above, §2.6). The situated cognition perspective therefore has an important message for those assessing learners (either as part of teaching, or researchers), as assessment activities are *situated* - that is the content and context of assessment activities have a strong effect on outcome (p.10).

It is worth pointing out here that, to borrow an aphorism, 'context is in the mind's eye of the beholder', for as Edwards and Mercer (1987) point out context is largely a mental phenomena that is not available to other people (pp.65-66). It is something that is "problematical" (pp.160-161).

In so far as Solomon's position is informed by notions of situated cognition she provides a way of explaining why the two perspectives outcome (§2.3.5) may be a consequence of teaching learners holding CHILDREN'S SCIENCE. However, Solomon also emphasises the *social* nature of knowledge construction (c.f. §2.2.2), and argues that whereas discourse is generally concerned with finding consensus and common understanding, in science very different norms apply.

§2.7.3: The social construction of consensual knowledge.

Solomon argues that "the process by which children construct notions for explaining the meaning of events in their daily life is *more social than personal*" (1993b, p.86). She points out that in the 'life-world' "it is taken for granted that others see things very much as we do", and we "expect to be able to understand each other and to share meanings" (p.86).

Solomon bases her argument on episodes from classroom discussion - collected during her own research - where she commonly observed an "unstated pressure" to resolve any disagreements (p.88), so that during a process of discussion contradictory opinions were often supported by the same children, with various assertions being put forward until some suggestion receives "social recognition". According to Solomon "familiarity wins the day" and unresolved disagreements were ignored (p.88).

As Solomon points out, this is not how scientific debate is meant to occur and the purpose of discourse is therefore different in the two domains, so that even a term such as 'explanation' takes on a different meaning - as "only in science ... does 'to explain' mean to fit the event into a metaphorical scenario" (1992, p.107). According to Solomon scientific knowledge is *by its very nature* less likely to be the domain of knowledge called-upon by most people in most circumstances. Her argument is that whereas "life-world knowledge is 'learnt' through social reaffirmation in everyday situations, the more esoteric knowledge of science is the product of school learning - a later, secondary process of socialization" (1992, p.112).

From this *social constructivist* position, Solomon has criticised the *personal constructivist* (or as Solomon would say *individual constructivist*) approach of workers such as Driver, Gilbert and Watts. She has argued that Driver's Kellyan notion of *the pupil as scientist* is untenable: and she proposes "three troublesome questions" that need to be asked of the *personal construction of knowledge* position (Solomon, 1993b, pp.85-6):

1. If children's notions have been assembled in such a logical, almost scientific way, why do school children then have such difficulty in understanding the logical method of science and resist changing their notions in the light of new and compelling evidence?
2. If they have tested their ideas in the different circumstances of daily life why is it that they apply them so inconsistently?

3. If every child is his or her own independent scientist, how is it that within a cultural group notions are so much more similar than they are across different cultures?

For Solomon these questions are not answered by Driver's (1983) notion of *pupil as scientist* but rather it is "the sharp contrast" between the ways in which knowledge is constructed in the two domains which acts as a barrier to the learning of CURRICULUM SCIENCE (Solomon, 1992, pp.37-38). She argues that the self-contradiction found in learners' ideas should deny them the label of CHILDREN'S SCIENCE (1994, p.9).

§2.8: A critique of Solomon's position.

Although Solomon's recent writings (e.g. her 1992, 1993a,b; 1994) criticise personal constructivism and establish an alternative position, it will be argued here that much of her work can be seen as compatible with the position taken by those researchers she criticises. There are some significant differences, and these will also be considered.

§2.8.1: The construction of scientific knowledge.

Solomon has emphasised the distinction between life-world and scientific knowledge, and has suggested that scientific modes of thinking do not come naturally to the untrained. The recognition that scientific thinking is something other than 'common sense' has recently been the basis of a book by Wolpert (a professor of biology as applied to medicine), who suggests that scientific thinking and common sense are "not congruent" and points out that brains have been selected by evolution for survival in the natural environment, and that the ways of thinking that evolved did not (for most of humanity's existence) involve formal scientific thinking (1992, p.11).

However, the metaphor of pupil-as-scientist does not rest on pupils being *accomplished* scientific thinkers. Indeed Driver, in her *The Pupil as Scientist?*, describes the limitations of student thinking (1983, pp.61). More recently Driver and coworkers have pointed out that "learning science involves being initiated into scientific ways of knowing" (Driver et al., 1994b, p.3) - a statement that reflects Solomon's position - and have carried out an extensive research project into pupils' understandings of the processes of science (Driver et al., 1996).

The personal constructivist position does not depend on learners following a particular scientific heuristic, nor being able to apply some objectively rational and logical analysis in their modelling of the world. Rather it is sufficient that learners spontaneously try to make sense of their world by constructing internal models to help them "predict and control" (Kelly, 1963 {1955}, p.5) their surroundings, and then being able to evaluate and modify these models as required (Pope and Gilbert, 1983, pp.196-197). It was in this sense that Kelly suggested one should explore the notion of 'man-as-scientist', not that all people were in some sense perfect scientists. Indeed, as Pope has pointed out, few professional scientists can claim to have been so objective,

> "For Kelly, the construction of reality is a subjective, personal, active, creative, rational and emotional affair; and if we are to believe modern philosophers of science, then similar adjectives can be applied to scientific theorizing and methodology."
> (Pope, 1982, p.6.)

Mahoney (1976) has suggested that many scientists use research methods which are "blatantly illogical" (p.153), something he attributes in part to the "logical fallibilities of individual scientists" (p.154). This author cites studies to demonstrate examples of such failings, and notes that as scientists are seldom given any formal training in logic, it is surprising that there is such a high expectation of the rationality of their work (p.154).

So the distinction between formal scientific thinking and 'life-world' thinking is neither so complete, nor so crucial as Solomon suggests. Indeed whereas Solomon wishes to emphasise the differences between children's learning and scientific thinking Strike and Posner put the opposite view,

> "questions having to do with individual learning have certain generic structural features, whether they concern a scientist struggling with a new idea on the forefront of knowledge or with a child trying to understand elementary concepts about motion"
> (Strike and Posner, 1985, p.213).

§2.8.2: The quest for common knowledge.

Another key point in Solomon's position is that the purpose of communication in science is to "sharpen differences" rather than to "try to achieve a mutual understanding" (1993b, p.92). Her point is that in professional scientific discourse debate takes on a dialectic nature, that correspondents seek to take contrary views to test out positions. In normal social chat the purpose is quite different - to achieve a consensus, and preserve social cohesion.

However, although the two 'purposes' Solomon identifies are distinct, they do not directly map onto 'scientific' and 'life-world' exchanges. For one thing people can on occasion seek to avoid consensus in the life-world rather than reach it. Solomon acknowledged examples of this in the classes she observed (1993b, p.88) and suggested that this usually occurred where there was animosity between the children concerned (p.88). However, this proviso could also be applied to the debate between Newton and Leibniz, which although conducted on scientific and philosophical grounds, is recognised to have been less motivated by a desire to further science, than by personal animosity (e.g. Park, 1988, pp.221). This ill-feeling arose from a priority dispute, one of many such disputes in the history of science (Mahoney, 1976, p.119). The desire for consensus and social harmony is not always present in either the scientific or the life-world domain.

Solomon's distinction between the two domains also fails in another sense. Ziman recognised the same pressure for consensus *in science* that Solomon claims characterises the life-world. He sees the aim of science as "a *consensus* of rational opinion over the widest possible field" (Ziman, 1978, p.3, my emphasis), and describes scientific knowledge as being the product of a social and cooperative process,

> "scientific knowledge is the product of a collective human enterprise to which scientists make individual contributions which are purified and extended by mutual criticism and intellectual co-operation"
> (Ziman, 1978, pp.2-3).

That is, scientific dialogue is characterised neither by the quest for disagreement nor agreement *per se*, rather both are part of a process of constructing public knowledge. Solomon herself seems to accept this when she reports that "scientific epistemology now rests on ... grounds which are social *and consensual* rather than objectively true" (1994, p.14, my emphasis), and opines that the solitary experiences of the knowing individual "will not do to describe either everyday knowledge, *or scientific knowledge*, or the learning of school science" (p.15, my emphasis).

Solomon's explanation of this discrepancy in her position seems to be that "science itself has been built up into a knowledge system by a consensual process *which is not that of the life-world*" (Solomon, 1994, p.16, my emphasis). Solomon acknowledges Ziman's work, and explains that science is a "corporate enterprise" and acknowledges that the scientific community has established means of monitoring the products of science (p.16). Yet it is difficult to see why this needs to be - *in principle* - a different process to that occurring in a discussion group set up in a school science class. Certainly the process would be different in degree, but not necessarily in type. Presumably the 'established ways of 'monitoring' the public constructions of scientific knowledge include observations of the natural world, and hypothesis formation and testing through experiment: the same ways that school pupils are being asked to monitor their own constructions in school science schemes developed from within the personal constructivist frame (Driver and Oldham, 1986).

Although the procedures of professional scientific activity do not match the social agenda of the school playground, nor do the activities that occur in a school classroom or laboratory. For example Edwards and Mercer note how school pupils recognise and accept that the world of the classroom has its own rules and agenda,

> "the principle, to put it crudely, that *lessons are about what happens in lessons* appeared to be a ground-rule that the pupils had themselves acquired"
> (Edwards and Mercer, 1987, p.78.)

In contrast Solomon suggests that for some children only familiar with the construction of knowledge in the life-world the presentation in science classes of the "harshly uncompromising" process of working towards scientific knowledge "amounts to an affront to the social mores" (1993b, p.100). However the work of Edwards and Mercer suggests that there is no problem here as both teachers and pupils understand the 'game' through which teachers lead their pupils to 'discover' the accepted public knowledge that makes up the curriculum. Pupils' conversations in the playground may reflect Solomon's social agenda, but in the classroom pupils would be expected to recognise that they are being asked to talk to a different purpose (although they may not be very skilled in carrying out the tasks). It has been suggested to me that a useful distinction to make might be between *knowledge* which might be constructed in classrooms though the dialectic of teachers questions and pupils responses, and *opinion* which may be transient, and constructed more through social consensus.

Materials produced by Driver's CLiS project contain samples of dialogue from secondary pupils discussing the merits of their scientific ideas. These examples of pupil talk do include agreements, but also many cases of pupils putting their alternative opinions, and challenging the previous speaker. There are also many examples where one pupil is clearly asking for clarification or further exposition of another's ideas, rather than just looking to agree or disagree. My reading of the extracts in Brook and Driver 1986, Johnston and Driver 1991, and Wightman et al. 1986, certainly suggests that much pupil discussion in science classes can *not* be explained *purely* in terms of the social imperative of the life-world.

One might ask how Solomon could interpret her classroom observations so differently from Driver and others. Perhaps she notices and emphasises different aspects of classroom talk because she is approaching her research from a different perspective (1993a). Whereas she characterises the personal constructivists as following the ethnographic approach, i.e. "to ask children to explain their ideas and then listen carefully to their words in the *verstehen* tradition" (p.1), she herself is working in a 'cultural effects frame', that is "concerned with the children's ideas about science *as reflections of the social influences and informal instruction which are at large within the community*" (pp.7-8, my emphasis). For example Solomon discusses one particular example where a pupil, Mark, had changed his lone opinion towards a general consensus view (that energy was stored in food),

> Whether Mark had achieved understanding, or had merely moved in order to 'stand in with the crowd', is impossible to tell. Possibly the question does not even have real validity *in the context of the social construction of knowledge* where several concurrent meanings exist and local communication is a major objective.
> (Solomon, 1992, p.76, my emphasis.)

The question Solomon refers to in this extract would be of crucial significance to a researcher *in the context of personal construction of knowledge*, as such a researcher would wish to know whether the pupil had genuinely come to agree with his peers, or had just wished to avoid a public disagreement. One can also ask which perspective has more significance for how the pupils will perform in tests when they have to work alone: i.e. unless the socially constructed knowledge becomes personal knowledge it will not benefit children when they are assessed in formal examinations. However, from a perspective where meaningful knowledge construction is about reaching a common understanding Solomon is able to ignore this issue.

So then for Solomon, the solitary experiences of the knowing individual "*will not do* to describe either everyday knowledge, *or* scientific knowledge, *or* the learning of school science" (Solomon, 1994, p.15, my emphasis). With respect to the research reported in this thesis, Solomon's perspective provides a useful warning not to over-interpret the significance of individual learners' utterances. However, for research that is based upon in-depth interrogation of individual learners, over extended periods of time, the ability of my colearners to present consistent, coherent and idiosyncratic pictures of their thinking - in the absence of a social group to reinforce a consensus - it is Solomon's emphasis on "consensus building" as "a process which might completely by-pass cognitive structures" (1992, p.75) which "will not do".

§2.8.3: Constructing knowledge in the classroom.

At this point it is illuminating to consider how constructivist perspectives on learning might inform classroom practice, as this is another area where Solomon has been critical of the alternative conceptions movement. Solomon would argue that as scientific knowledge is "harshly uncompromising", the teacher's role is to direct the pupils to "make the imaginative but agreed pictures of consensual science their very own" (1995, pp.16-17) through questions "designed to elicit the right answer" (1992, p.132).

Edwards and Mercer point out that questions are components of "the discursive weaponry" that teachers use to direct classroom discussion towards the intended "common knowledge" (1987, p.46). They describe education as "essentially a process of cognitive socialization through language" whereby classroom discourse is used for "introducing pupils into the conceptual world of the teacher and, through her, of the educational community" (p.157). Part of the teacher's role is to assist pupils to take up as their own the desired vocabulary, and the selected descriptions and explanations that will form the "basis of joint understanding" (p.151).

This perspective may be compared with a *naïve* personal constructivist approach that given the right classroom experiences the learner will personally construct the desired knowledge. It is unlikely that this has ever been seriously proposed as an unproblematic process. The CLiS project was devised to "develop revised teaching approaches which would be informed by research on children's thinking in science and current theoretical developments in cognition" (Driver and Oldham, 1986, p.105). These approaches would involve (p.108):.

- devising learning materials which take account of students' prior ideas;
- developing ways of working in classrooms which encourage students both individually and collectively to become active in the learning process;
- making explicit the implications of adopting a constructivist perspective for classroom practice.

A basic tenet of this approach was that the curriculum should be a programme of activities which encourage pupils to (re)construct scientific knowledge (p.112-6). The teacher's role was to be a "facilitator" who would provide the appropriate opportunities for the pupils to undertake the construction (p.116). The constructivist model proposed included elicitation of ideas, and the restructuring of ideas - including exposure to conflict situations and construction and evaluation of new ideas (fig.3, p.119).

Solomon has pointed out that for a teacher to be aware of learners' ideas is not the same as having a means of bring out the desired changes (1994, p.10). Whilst acknowledging that CLiSP had produced "a rich source of valuable data" she still found it difficult to understand what was meant by 'constructivist teaching' (p.11).

Such an approach to curriculum planning and development is based on a view of learning as conceptual change (Driver and Oldham, 1986, p.117), a view that has been considered by a number of workers (see Gilbert and Pope, 1986a; Nussbaum and Novick, 1982; Strike and Posner, 1985). The approach discussed by these authors is to ensure students are aware of their ideas, then to challenge them with experiences that do not match their expectations (to produce what is variously called 'disequilibrium', 'cognitive dissonance', 'cognitive tension' or 'conceptual conflict') so that the learner will be motivated to test alternative models that do not conflict with experience.

Solomon has criticised constructivist teaching approaches on the basis that individual learners may have no stable alternative frameworks for a topic, yet the classroom activities intended as elicitation provide just the social context where the construction of *alternatives to* science will take place. Solomon also points out that interviews - so commonly used in constructivist research to elicit learners' ideas - are not part of the normal teaching repertoire (1994, p.10); but this is confuse research and teaching, and ignores the ability of interviews to remove the learner from the very social milieu that Solomon considers the trigger for learners' alternative ideas.

Even if Solomon were correct that the 'elicitation' process in constructivist teaching schemes is actually a 'construction' of alternative theories, this may not negate the approach, as Ault, Novak and Gowin had found that that the acquisition of a complex scientific concept seemed to be more likely where the learner had been able to produce a range of relevant ideas at an early stage (see §2.3.11). In particular, they found that it was not important if the learner's initial ideas were incorrect from a scientific viewpoint, as long as there was 'rich conceptualisation' on which to build,

> "what matters most in the improvement of understanding is not simply the accuracy of conceptualisation, but the richness; not the sequence of acquiring new meanings, but the concerted effort to reconcile new with old; not the characterization of children's understanding chronologically, but the teaching of concepts by *someone who takes time to find out* how children modify meanings conveyed, how they apply concepts to make sense of events, and how they arrive at the claims they make"
> (Ault, Novak and Gowin, 1984, p.460, my emphasis.)

Although Ault and coworker's comments appear to negate Solomon's concerns, her doubts about 'constructivist teaching' is shared by Millar, who *does* believe in the individual's *personal* construction of knowledge. Like Solomon, Millar has pointed out that taking learners' ideas seriously needs to be reconciled with science as (at any one time) a body of knowledge that is to a great extent consensually accepted by the scientific community (1989, p.588). Millar's acceptance of the construction of knowledge as an *intra*personal process leads him to *not* automatically preclude particular teaching approaches. If the construction of knowledge is a mental process within an individual's mind, then a traditional method such as 'chalk and talk' might on occasion provide a suitable impetus to conceptual change,

> "the process of eliciting, clarification and construction of new ideas takes place *internally*, within the learner's own head ... independent of the form of instruction"
> (Millar, 1989, p.589.)

(It might be noted here that Ausubel (1961) has similarly pointed out that meaningful learning (§2.2.5) in adolescent learners does not rely on 'discovery' methods, and indeed he suggests that verbal reception learning can be the most efficient way of meaningfully learning subject content.)

Millar concludes that "science should be taught in whatever way is most likely to engage the active involvement of learners" (p.589). However he points out that all learning involves the learner in reconstructing knowledge internally (p.592), and - unlike Solomon - he recognises the value to this process of the type of activities recommended by Driver and Oldham,

> "the classroom activities suggested by the constructivists for eliciting, clarifying and reconstructing ideas become immensely valuable for the teacher who is monitoring and managing this reconstruction process"
> (p.592.)

§2.8.4: Personal construction within a cultural context.

The third of Solomon's questions to the personal constructivists was "if every child is his or her own independent scientist, how is it that within a cultural group notions are so much more similar than they are across different cultures?" (1993b, pp.85-6). Solomon points out that the nuances which words carry vary in different languages, and that this may be related to some of the alternative conceptions associated with such words in different cultures (1993b, pp.89-92) as ideas leave 'imprints in the language' (1992, p.168). The importance of words *as tools of thought* was emphasised by Vygotsky (see above, §2.2.2), and in-so-much as different languages use different words and word-meanings and therefore "cut up the world in different ways" (in Kuhn's expression, 1970 {1965}, p.268), it is quite reasonable to expect them to channel thinking differently. Indeed as Polanyi pointed out, different languages "sustain alternative conceptual frameworks" (1962 {1958}, p.112).

A learner's cognitive structure may be viewed as much a part of the learning environment as other factors. Hewson refers to Toulmin's notion of 'conceptual ecology' where concept formation is interpreted according to "the varied mental sets of individuals which are a function of their *intellectual* and physical environment" (1985, p.153, my emphasis). This idea is also used by Strike and Posner who suggest that "understanding entails finding a niche within a conceptual ecology" (1985, p.219). They list the following as features of such a conceptual ecology: anomalies, analogies and metaphors, exemplars and images, past experience, explanatory ideals, general views about the character of knowledge, metaphysical beliefs about science, metaphysical concepts of science, knowledge in other fields and competing conceptions (pp.216-217). It will be seen that language has a role to play in many of these features.

In my view Solomon's question of the personal constructivists is misguided as it appears to imply that a commitment to personal construction of knowledge assumes the learner-as-scientist will be able to develop theories of the world based on experience of the *physical* world unmediated by cultural factors. This has never been the assumption: and Driver points out the inadequacy of such Baconian naïveté as early as page 4 of her *"The Pupil as Scientist?"* (1983). Solomon questions the child-as-independent scientist, whereas Driver clearly wrote about the pupil-as-*scientist working within a community of scientists*: "science as a cooperative exercise *as opposed to an individual venture*" (p.4, my emphasis). Although Hewson was writing some years *before* Solomon posed her question, the following quotation might stand as a response to Solomon's inquiry,

> "The intellectual environment in which a person lives (including cultural beliefs, language, accepted theories, as well as observed facts and events) favors the development of some concepts and inhibits the development of others. Thus the intellectual environment acts as an ecological niche."
> (Hewson, 1985, p.154.)

§2.8.5: The value of Solomon's critique - learning science as cognitive apprenticeship.

Although it has been argued that Solomon's perspective does not undermine the basic tenets of the (personal) constructivists, her emphasis on the role of social interaction may have been influential in emphasising this aspect of the individual's learning environment. Certainly writers such as Edwards and Mercer, and Hennessy, have put emphasis on the role of the teacher in providing the structure - in a Vygotskyan sense, that is "through a series of processes such as modelling, coaching, scaffolding, fading, articulation" (Hennessy, 1993, p.11) - to encourage the desired construction of knowledge. So, as Hennessy says,

> "expertise is acquired through both the spontaneous invention of personal, highly efficient procedures in response to the needs of a situation, *and* through apprenticeship"
> (1993, p.15, my emphasis.)

Hennessy explains this notion of apprenticeship as involving "providing help in developing an appropriate notation and conceptual framework for a new or complex domain and allowing the learner to explore that domain extensively, then gradually withdrawing support" (p.12). Through this process the learner will develop "tacit strategic knowledge" both cognitive and metacognitive. This will include strategies for exploring new domains of knowledge, and for '*reconfiguring*' knowledge in a topic area (p.20, my emphasis).

The position of Driver and her coworkers has developed somewhat to take such perspectives into account, so that the teacher's role not only includes providing physical experiences and encouraging reflection, but giving learners access to what they have called the "*symbolic realities*" or "cultural tools" of science" (Driver et al., 1994c, pp.4-5, my emphasis). This evolved constructivist perspective means that teachers should not just expect pupils to demonstrate alternative conceptions, but possibly multiple conceptual frameworks which are appropriate to different contexts (p.5).

The *social constructivist perspective* has been emphasised in the new presentation of the personal constructivist position, so that learning is seen to involve induction into the 'symbolic world' of science (p.5) as well as the social interaction in the classroom setting (p.6). Constructivist teaching still involves "challenging learners' prior ideas through discrepant events" but is also recognised as socialisation (c.f. Edwards and Mercer, 1987, see §2.8.2),

> "young people entering into a different way of thinking about and explaining the natural world; becoming socialised to a greater or lesser extent into the practices of the scientific community with its particular purposes, ways of seeing and ways of supporting its knowledge claims"
> (Driver et al., 1994c, p.8).

§2.9: Degrees of integration in cognitive structure.

From the literature reviewed it is possible to develop a position which gives heed to the various perspectives discussed, and which does not unnecessarily limit the interpretation of the data collected as part of this research.

It is considered here that people *can* construct within cognitive structure extensive, largely coherent and consistent, frameworks of ideas (and there will be evidence for this presented in chapters 7 onwards). These frameworks may be analysed in terms of components at the level of conceptions - but the various conceptions *are* related through the framework.

However, it is not claimed here that *all* knowledge held by *all* people *is* structured in this way. As Claxton suggests (§2.6), knowledge *may* be stored as *substantially discrete* parts, as in his mini-theories, thus explaining the characteristics of research data that do not support the presence of 'frameworks'.

In other words, an overview of the research literature would lead to an assumption that there are different possible *degrees of integration* of knowledge held in cognitive structure. An 'ideal', totally integrated, representation of an individual's knowledge would have all its components inter-related though a logical, self-consistent set of links. At the other extreme would be the storage of knowledge as a random catalogue of totally independent fragments - as in Claxton's "store of amazing facts". Real cognitive structures would be between these extremes, and the *degree of integration* of knowledge in a subject area should be a major concern for teachers and researchers (c.f. §1.5.2). The integration of some new 'piece of knowledge' into the structure would depend upon the level of integration and coherence of the existing material, and the perceived relevance of the new information to existing knowledge (§2.2.5). Degree of integration is one factor affecting the likelihood of learning impediments occurring during instruction (§1.5.2). The degree of integration of my colearners' ideas related to chemical bonding is one of the factors investigated in this research (see the case studies in chapters 7 and 8).

§2.9.1: Interpretations of multiple frameworks.

Accepting the possibility of degrees of integration within cognitive structure, then there are four possible interpretations of *multiple frameworks* (§2.5.2). If a researcher's data *suggests* that a learner holds two or more frameworks to explain the same phenomenon, then this could be because:

1) the learner's mental representation of the concept is unified and consistent, and consequently 'multiple frameworks' demonstrate inadequacies in the researcher's models (c.f. Pope and Denicolo 1986, see §2.5.2);
2) the learner may not represent his or her knowledge of the topic in coherent and self-consistent terms, but rather as a range of discrete knowledge fragments: the researcher *over-interprets* a learner's utterances as a set of conceptual frameworks due to his or her assumptions about cognitive structure (c.f. Claxton, 1983, see §2.6);
3) multiple frameworks reflect a genuine aspect of the learner's cognitive structure: learners can have alternative versions of 'the same' concept - and this may be seen as due to a lack of integration of concepts, and an immature stage in conceptual development (c.f. §2.6.1);
4) multiple frameworks reflect a genuine aspect of the learner's cognitive structure: learners can have alternative versions of 'the same' concept - and this may be seen as an *appropriate adaption* by

the learner to the different contexts in which the ideas may have to be applied (see §2.7.2).

All four of these possibilities are feasible, and they should not be seen as mutually exclusive positions. It is possible all four options occur (and may quite likely be represented in the literature). An awareness of these possibilities has informed the analysis of data collected in this present study.

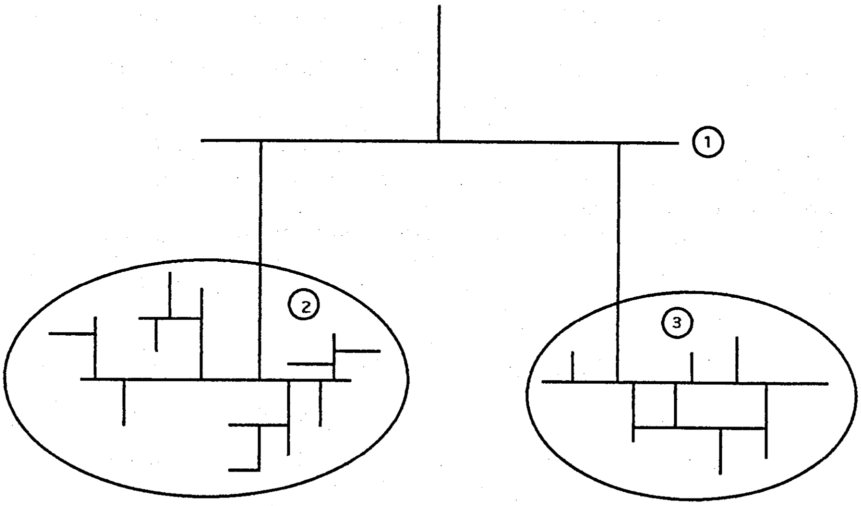
Where the multiple frameworks are authentic, they may represent an appropriate level of understanding in view of the nature of chemical knowledge (see chapter 1, §1.3.1, §1.7.1). However, they may also provide indicators by which to measure progression, especially where the frameworks do not match the CURRICULUM SCIENCE models (see §8.4.3).

§2.9.2: Shifting between alternative frameworks.

The possibility of learners' holding several frameworks for explaining a phenomenon does not rely on the learner being aware of the context-dependence of knowledge - it is not suggested that the learner necessarily *consciously* makes a decision to apply a life-world or an academic framework for thinking about, say, force. Indeed it would seem more likely that this is a tacit process influenced by a whole range of factors (who posed the question, how formal was the language used, in what location and situation the question was asked, etc.) The key point is that the learner has ***distinct*** alternative frameworks for thinking about what - to the researcher - is a single concept area.

Yet it is clear that such shifts between different frameworks of thinking do occur. For example the historian comparing how an event would be interpreted in the conceptual schemes ascribed to Aristotle, Galileo and Newton would need to be able to shift between the schemes (each of which must be represented in his or her own cognitive structure). The educational researcher needs to be able to shift into the model of the learner's thinking to try to understand what the learner means by his or her utterances. Kelly referred to subsuming the constructs of the other into one's own system (1963 {1955}, p.174), and this implies some sort of hierarchical arrangement of constructs, so that one may shift between frameworks by moving to a higher level of the construct system - perhaps what Pope and Denicolo refer to as "the system of necessary interrelationships" of "component intuitive theories" (1986, p.158). I have represented this diagrammatically in figure 2.1.

figure 2.1 - a model of alternative frameworks embedded in a cognitive structure



1. a supersuming level of cognitive structure which allows the learner to switch between alternative frameworks for thinking about a concept.

2. and 3. two distinct parts of a learner's cognitive structure, which may be understood as alternative frameworks for thinking about a concept area.

In this diagram the areas labelled as 2 and 3 represent some parts of cognitive structure assumed to represent knowledge in *self*-consistent ways - i.e. conceptual frameworks. However the knowledge represented in 2 need not be consistent with that represent in 3, because transfer between these regions is mediated by a link at a higher (more abstract perhaps in Kelly's terms) level in cognitive structure.

This model for the process might be seen as analogous to the idea of a metalanguage which allows one to discuss language. Although thinking within one region of the cognitive structure is constrained (channelled) by the logic of the constructs in that region, it is always possible to move outside that logic *via* a more abstract level. Without some such mechanism there would be no imaginative leaps, which are essential for the act of discovery - even at such a mundane level as understanding the punch-line of a joke (Koestler, 1978.)

§2.10: Conceptual change.

As the true nature of cognitive structure remains unknown, it is not possible to know exactly how conceptual development can occur (and models such as that presented in figure 2.1 above and fig. 2.2 below are conjectural, although they may have considerable *heuristic value* in guiding research). For one thing, there is no precise agreement on what a concept is (see §2.10.2 and §4.7.2), and therefore how it should be understood to be represented in cognitive structure.

§2.10.1: Two types of conceptual change.

Conceptual change may be considered to be of two types. Firstly, a great deal of learning may be understood as 'local', in that it concerns a small addition to, or alteration of, knowledge, which - *to a first approximation* - has no repercussions for overall conceptual structures. Secondly there is learning which has greater ramifications: changes in perspective that fundamentally alter the perceived relationship between different concepts held in cognitive structure, and suggest that some form of major reorganisation is required (e.g. Novak, 1985, p.193-194). For example, Ault, Novak and Gowin found that sometimes "acquisition of a key concept causes a *significant shift at a number of levels* in the organisation of conceptual understanding" (1984, p.459, my emphasis).

Probably much learning is actually intermediate in nature (Strike and Posner, 1985, p.216), but these two classes of change, akin to *accretion of knowledge* and *conceptual revolution*, suffice to stand for the spectrum of conceptual changes learners undergo. Although different workers have chosen to give various labels to these two categories, (for example, Ault et al., refer to *progressive differentiation* and *integrative reconciliation*, 1984, p.460) they may be seen as derived from Piaget's distinction between *assimilation* and *accommodation* - that is "incorporation of new objects and experiences into existing schemas" and "modification of schemas as a result of new experiences" (Beard, 1969, p. ix) respectively. The former type of change can readily be modelled, but the latter, is more problematic. Thagard's model of conceptual change is discussed below (§2.10.6), and his approach to modelling these two types of conceptual change is described in appendix 9 (§A9.2).

§2.10.2: The relational view of concepts.

Gilbert and Watts criticised what they labelled the 'classical' view of 'concept' - that is "that all instances of a concept share common properties and that these properties are necessary and sufficient to define the concept" - as a gross oversimplification based on an assumption that knowledge is arranged hierarchically in discrete layers in the mind (1983, p.65). They identified this approach as - in Kelly's terms - 'accumulative fragmentalist' (p.65), and suggested it leads to a research programme of spotting bugs in the system, that is 'misconceptions' (p.66, c.f. §2.3.1). They preferred an alternative 'actional' view of concepts (p.66, c.f. the 'theories-in-action' of Driver and Erickson, 1983, §2.6). They also acknowledged an intermediate 'relational' view, where conceptual structure took the form of a network (p,68), which enabled concepts, to have borderline cases (p.67). (In the present research one might give the example of *the extent to which* van der Waals' forces are included in the concept of the chemical bond.) However, Gilbert and Watts did not feel that the relational model could explain more radical reorganisations of knowledge (i.e. accommodation, §2.10.1).

One might suggest that a learner's developing concept of the chemical bond could largely be modelled from the relational view, that is, as,

> a person's experiences accumulate, a concept changes in the number of exemplars and their degree of membership but remains essentially the same concept in terms of its internal features and its external links. (Gilbert and Watts, 1983, p.68.)

If cognitive structure is viewed as a network, then the meaning of a concept depends upon the whole network of propositions that it is part of, so that if any connection is altered, the meanings of all the interrelated concepts shift to some extent (Phillips, 1987, p.206). This perspective is referred to as 'semantic holism'. The development of the chemical bond concept to include hydrogen bonds might be conceptualised in these terms. The learner's cognitive structure may be understood to include a network of propositions relating to chemical bonding. The assimilation of the hydrogen bond concept into the subsuming chemical bond concept (by adding a new proposition - *hydrogen bond is a type of chemical bond* - to the network) would change the meaning of 'chemical bond' to the learner. To the extent that the concept 'covalent bond' is connected in this network its meanings would also shift (though in this case the change in meaning is more subtle). Gilbert and Watt's criticism was that such a model would not seem *sufficient* to explain more radical reorganisations of knowledge (p.68): an example might be how a learner might accommodate a new theory of bonding based on molecular orbital theory, or how a learner might switch from seeing covalent-ionic as a dichotomy to a continuum (see appendix 4 for an analysis of how the bonding concept might be developed during an A level course).

§2.10.3: Models of conceptual change.

A number of workers have tried to explain conceptual change as a rational process, based on decisions about the relative merits of different conceptions (§2.10.5). Gilbert and Watts (1983) considered several approaches to conceptual change.

One perspective is analogous to views of evolutionary (i.e. Darwinian) development, and had been applied (by Toulmin) to historical development of scientific concepts. In this model there is a continual generation of conceptions, some of which are selected for (as they show greatest value in problem solving) and retained, whilst most are discarded (Gilbert and Watts, 1983, p.89). Again such a perspective could not explain the radical conceptual changes of *accommodation* (p.68).

Gilbert and Watts discussed a 'catastrophe theory' model of conceptual change, which could explain the more 'revolutionary' changes in a learner's thinking (an approach since discussed by Boyes, 1988). This is basically a cost-benefit model: an existing notion is held until the point is reached where the benefits of change outweigh the cost (Gilbert and Watts, 1983, p.91). The catastrophe theory model was seen by Gilbert and Watts as having the most potential as it could explain both gradual and sudden shifts in ideas. A possible difficulty with such a perspective is that an alternative view is only accepted if it is seen to be advantageous, but until it has been built up and explored it is unlikely to be judged as a serious competitor for a view that is already held and grounded in one's experience. This objection can be overcome if one distinguishes between *the construction of a perspective*, and the *acceptance and belief* in that view (Driver and Bell, 1986, p.451), and if one accepts that people readily construct inconsistent notions into their cognitive structures.

If a learner's entire conceptual structure was required to be to be unified, consistent, coherent *etc.*, this might lead to a very inflexible approach to learning. Once a conception had been acquired and represented in cognitive structure, it would not be possible to accept any contrary conception without discarding the original. Any two conceptions which are inconsistent in terms of the whole system of logical relationships would not be tolerated in structure at the same time. This would require a highly effective 'logic checker' monitoring the entire knowledge structure, and some sort of 'decision unit' that could decide which conception to jettison. When new information apparently contradicts existing knowledge, an immediate decision, to ignore the new idea or to discard an existing conception, would be needed for an individual's mental representation of a concept to remain unified and consistent. In view of the imperfections in our ways of coming to knowledge such a cognitive system would be highly inflexible: in a world where the information available is often incomplete or seems contradictory it would also be highly inefficient.

Alternative approaches suggest how learning may take place in such a 'fuzzy' information environment. If inconsistency is tolerated it is possible to consider alternative possibilities *until* there is judged to be sufficient evidence to make an informed choice between them. In the meantime the consequences of the alternatives can be explored. (This raises interesting questions as to the extent to which such processes are subconscious, systematic, intermittent, prioritised by current concerns, etc.)

A model of cognitive structure which *enables* knowledge to be stored in discrete fragments allows us to understand how we may learn about two apparently separate phenomena, and then later come to know that the two are connected, and are aspects of some superordinate concept. The lack of coherence in learner's ideas that has been commented upon by some researchers (such as Claxton, §2.6), can be understood as separate storing of ideas as *discrete* conceptions, or as parts of *distinct* conceptual frameworks. This has particular significance for the present research, as for example when covalent and ionic bonding come to be understood as extremes of a single model (rather than explained by distinct models) or when intermolecular bonding and atomic binding are understood to be due to the same basic physical forces as intramolecular bonding. At the point where the two fragments become related in cognitive structure it is possible that inconsistencies and contradictions will come into being. This is illustrated schematically in figure 2.2.

Part (a) represents two discrete conceptual frameworks ① and ②, each comprising of a set of internally consistent conceptions. In (b) the learner has acquired a new conception which links ① and ②, and which enables him or her to start to perceive them as aspects of the same concept. At this point there may be inconsistencies in the new conceptual framework as parts of ① and ② are not logically compatible. Part (c) reflects a later time when the learner has changed some of the propositions that were components of ① and ②, so that they are consistent; and has explored the new unified concept area ③, and discovered further connections that were not apparent when ① and ② were perceived as unrelated.

figure 2.2 - a model of two inconsistent knowledge fragments stored in cognitiv structure being connected, then 'integrated'.

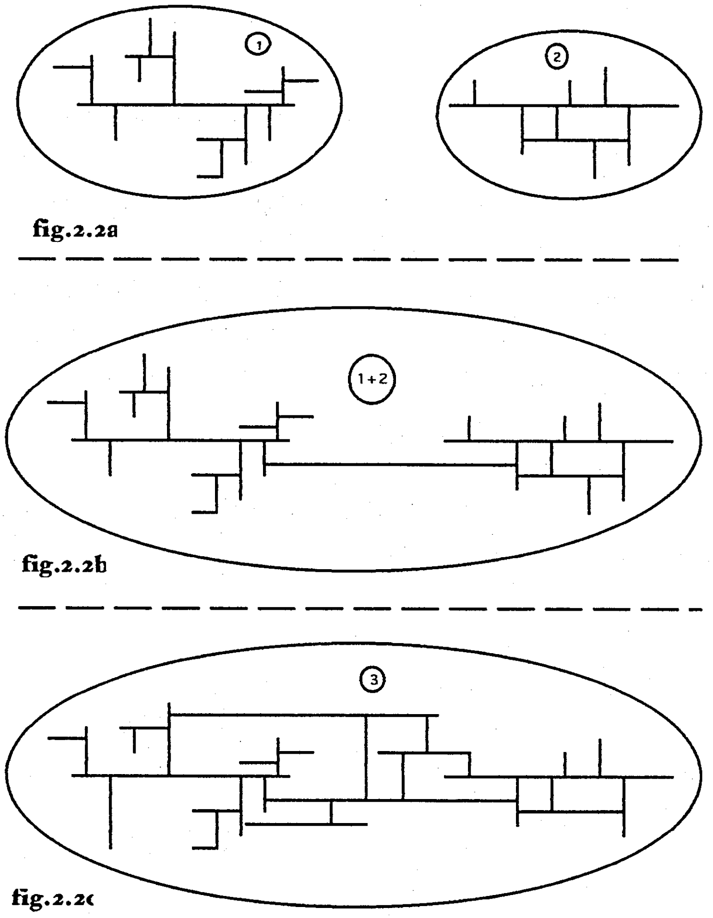


fig.2.2a

fig.2.2b

fig.2.2c

As an example, ① might represent a learner's ideas about gravity, and ② her ideas about orbital motion. She might be told, and accept, that satellites remain in orbit due to gravity, and thus a link is made between these two frameworks of knowledge that will *in time* lead to an enlarged framework of knowledge about gravitation (③) which incorporates most of her old ideas about gravity and satellites that were previously considered unrelated. In the model, when the link *is first made*, and *before* there has been any opportunity for other changes in ① and ②, there are inconsistencies in the combined framework. Perhaps ① includes a conception that gravity makes everything fall to the ground, and ② that objects stay in orbit forever. Clearly one or other or both of these conceptions must be altered before the new framework can be considered logically coherent.

Note that in this model there are times when the learner holds multiple 'partial' frameworks for a concept area (fig.2.2a), and during the process of integration inconsistent propositions are part of the same framework (fig.2.2b).

§2.10.4: Modelling learning impediments.

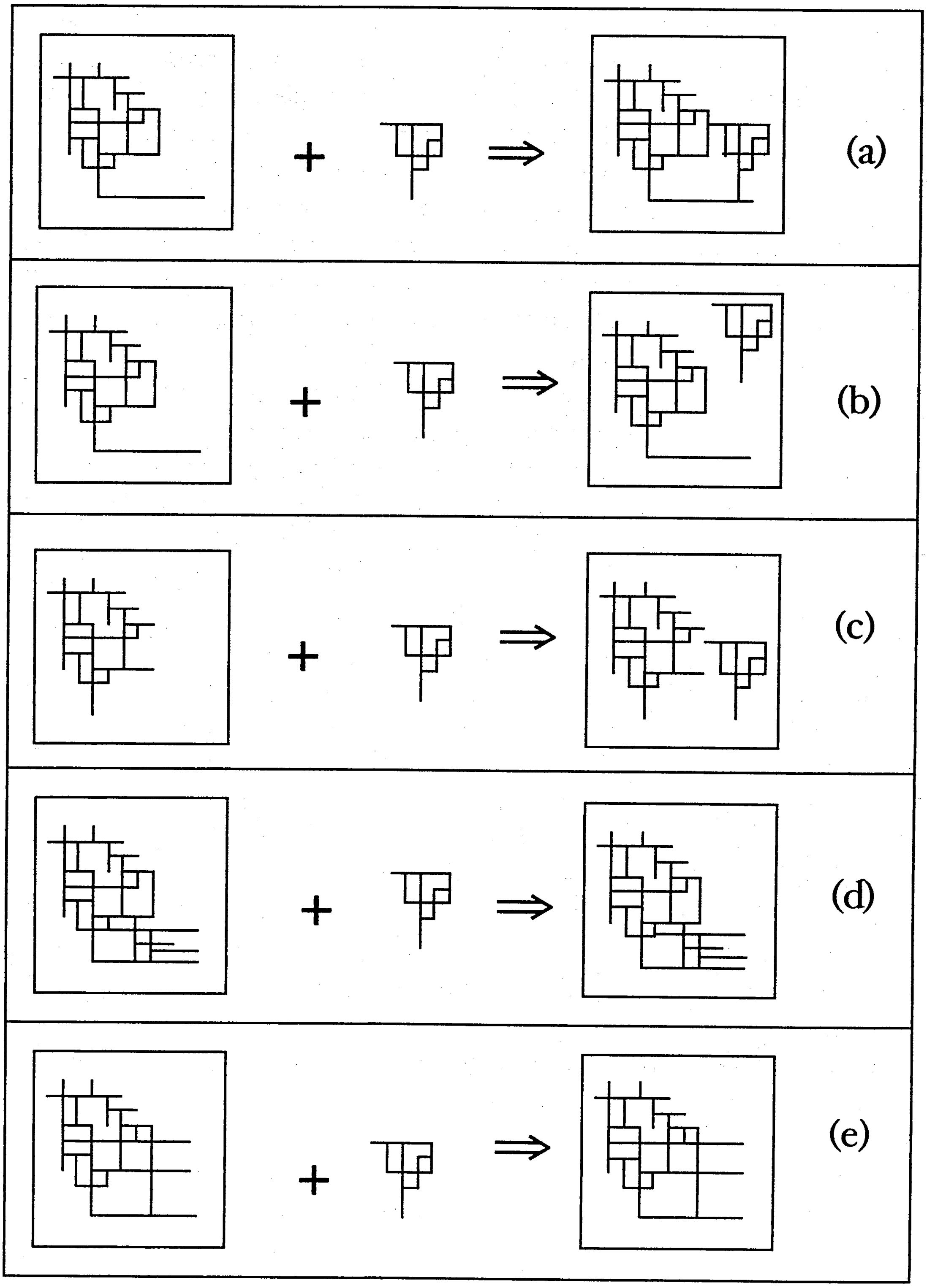
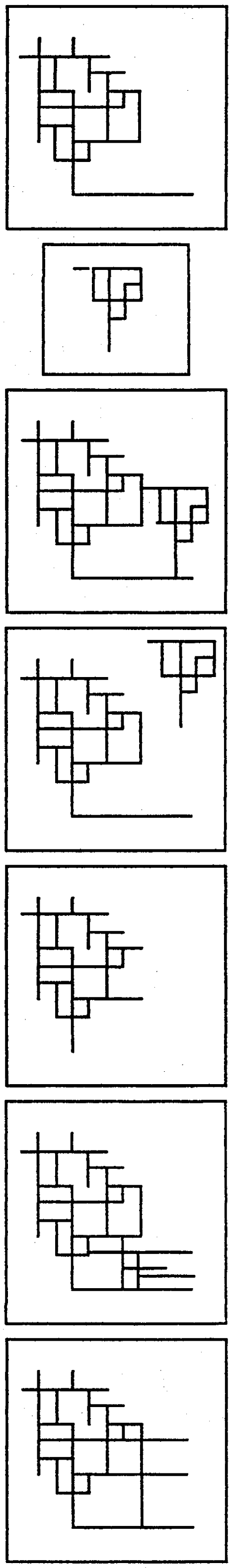


figure 2.3: a model of learning and learning impediments

(a) effective learning; (b) fragmentation learning impediment; (c) deficiency learning impediment; (d) ontological learning impediment; (e) epistemological learning impediment.

A similar type of diagram may be used to model the various aspects of a learner's cognitive structure that may act as learning impediments (§1.5). Figure 2.3 models an example of effective learning in comparison to the effect of the four classes of learning impediment.



In this diagram the square at the left of the figure represents a small part of a learner's conceptual structure (shown as a discrete fragment for the sake of simplicity). In part (a) it is assumed that the learner's prior knowledge matches the desired prerequisite learning for the topic.

The symbolism shown as being added (i.e. "+") in the figure represents the conceptual structure of the related segment of curriculum science that the teacher intends to teach.

In (a) the desired learning takes place, and the square at the right of the diagram represents the 'target' conceptual structure with the new knowledge extending the existing prerequisite knowledge (which is shown otherwise unchanged, for the sake of clarity).

In (b) the learner has the required prerequisite knowledge structure, but does not *perceive* the teacher's presentation as relevant to any previous knowledge. A FRAGMENTATION LEARNING IMPEDIMENT means that *at best* the new knowledge will be learnt as an isolated fragment.

In (c) the learner does not already hold all of the required prerequisite knowledge needed to make sense of the teacher's presentation in conceptual structure. A DEFICIENCY LEARNING IMPEDIMENT means that the intended links can not be forged.

In (d) the learner holds the intended prerequisite knowledge, but already has alternative conceptions relating this to the new topic area due to intuitive theories. An ONTOLOGICAL LEARNING IMPEDIMENT interferes with the intended learning.

In (e) the learner holds prerequisite learning, but due to misinterpreting previous teaching already has alternative conceptions relating this to the new topic area. An EPISTEMOLOGICAL LEARNING IMPEDIMENT interferes with the intended learning.

The situations shown as (d) and (e), the SUBSTANTIVE LEARNING IMPEDIMENTS, are very similar (I have represented the former with additional links, and the latter with extended links, but this is somewhat arbitrary). It is possible that sometimes in this situation the learner may replace the inappropriate conceptions and form the target structure. However on other occasions the learning impediment may be only partially overcome, or may lead to fragmented learning, or - as in the diagram - no learning (c.f. 2.3.4).

§2.10.5: Rational criteria for conceptual change.

In the model represented, the two distinct areas of cognitive structure in figure 2.2 were referred to as multiple 'partial' frameworks, as initially they were perceived as relating to separate concepts by the learner, but subsequently they reorganised into a single framework. It is possible to consider the situation where the two distinct frameworks were not unified (in the example, the learner did not come to see orbital motion as a gravitational phenomenon), but each developed until they both described and explained much the same range of phenomena. In such a case the two frameworks might come to have many similar elements, as well as aspects that were inconsistent. The learner would have available multiple frameworks for interpreting those phenomena within the range of both frameworks. (Perhaps sometimes one framework is based in everyday experience, or 'lay' science terms, and the other based on formal instruction, as discussed above, §2.3.5, §2.7.1, §2.7.2).

One could conjecture that whether partial frameworks are subsumed into an integrated structure, or developed extensively in parallel, is likely to depend on the point at which there is 'recognition' (by which I do not necessarily mean consciously) that the two frameworks are closely related: if this occurs *before* there is a good deal of redundancy between the frameworks the 'benefit' of the few changes needed for integration may outweigh the 'cost'. If the two structures are extensive when the realisation occurs, the disruption and effort of a major restructuring may not be justified. In this situation it is possible that multiple frameworks will be retained indefinitely, perhaps each accessed according to different contextual cues (c.f. §2.7.2).

Ausubel's meaningful learning theory (§2.2.5) and Kelly's theory of personal constructs (§2.2.4) would suggest that individuals *are* - in principle at least - motivated to make sense of their worlds. However, presumably, there is some 'effort' involved in undergoing conceptual change. This is certainly true in a physical sense (in terms of energy and entropy considerations). In terms of Kelly's P.C.T. (see above) the ease with which conceptual change may occur depends upon a feature of a person's constructs referred to as 'permeability', so that "the variation in a person's construct system is limited by the permeability of the constructs within whose range of convenience the variants lie' (*Modulation Corollary*, Kelly, 1963 (1955), p.77). According to Kelly's scheme, a construct is permeable "if it will admit to its range of convenience new elements which are not yet construed within its framework", and there are "relative degrees of permeability and impermeability" (1963 (1955) p.79).

Strike and Posner (1985) have suggested that learning should be considered "a rational enterprise", where rationality is concerned with the conditions that should lead someone to change his or her mind (p.211). These conditions involve judging how well competing conceptions match empirical evidence, can explain experience, meet metaphysical assumptions about the form explanations should take, and are consistent with other knowledge (pp.212-215).

Strike and Posner suggest four conditions that must be satisfied before *accommodation* will occur (p.216; see also Thorley and Stofflett, 1996, for a discussion of these factors). Firstly the learner must have reason to be dissatisfied with existing conceptual schemes. They point out that accommodation is unlikely if existing frameworks can be made to work with minor adjustments (p.216). Secondly the learner must have 'minimal' understanding of the new conceptions, so that it's potential for explanation may be explored. They suggest that this involves being able to relate the new conceptions to some existing part of cognitive structure, and to familiar examples from experience (pp.216-219). Their third criterion was that the new scheme should seem a plausible alternative because it can be seen to explain the apparent discrepancies in the present scheme, and it meets metaphysical expectations. Finally the new conceptions should seem to be 'fruitful', in the sense that they suggests the possibility of wider explanatory scope (p.216).

§2.10.6: Explanatory coherence: an example of a specific model of conceptual change.

In the literature reviewed so far the discussion of conceptual change has dealt with general principles. Thagard (1992) has produced a model based on similar principles to Strike and Posner, using the criterion of 'explanatory coherence' to determine when conceptual change would be expected.

Thagard's approach was primarily developed to analyse historical examples of conceptual change (see appendix 9, §A9.3) - to "understand the structure and growth of scientific knowledge" (p.3) - however he considers his approach to apply to contemporary learners of science as well as scientists of historical standing. His particular computer model assumes knowledge is arranged hierarchically - which may not always be the case (§2.10.2), but it is a useful example of how the general principles discussed above may be built into a functioning model that replicates conceptual change. (More detail of Thagard's model is given in appendix 9).

Thagard sees the personal construction of models of *alternative* scientific theories as a step in a rational process of paradigm shifts. The scientist - or young learner - holds one theory, but gradually builds up an understanding of, and familiarity, with an alternative. If the alternative comes to be seen as having greater *explanatory coherence* then it will become the preferred theory with which to operate in that domain. (Thagard's criteria for explanatory coherence are discussed in appendix 9, §A9.5.) Thagard describes how a scientist exposed to an alternative theory to the one held will construct a model of the theory 'in the background' to compare with his or her original (p.60).

For example when chemists learnt enough about the oxygen theory to believe it had *greater explanatory coherence* than the phlogiston theory, they changed to the new theory. For this to happen they had to be instructed in the new theory, but also had to have time to construct and explore, or read about and reflect on, the arguments in favour of the two alternative theories: "setting up the requisite nodes and links, was not enough: people had to use the new system enough to appreciate its power" (p.59). Thagard considers this to be a process which may take years. Priestley's rejection of the oxygen theory may be considered rational if it is understood that as the "preeminent phlogiston theorist" he had developed over many years the most elaborate and coherent conceptual scheme based around the phlogiston concept and therefore he never explored the oxygen concept enough to appreciate that it had greater potential (pp.59-60).

Thagard suggests similar processes *may* be operating in children, and conjectures that when they learn enough about an aspect of curriculum science to "*consciously or unconsciously*" appreciate it has greater explanatory coherence than their CHILDREN'S SCIENCE they will switch to using the taught version (p.258).

Like Novak, and Strike and Posner, Thagard distinguishes two types of conceptual change (his taxonomy of epistemic change is reproduced in appendix 9, §A9.4). He considers adding or substituting a single concept or rule as relatively trivial, whereas 'revolutionary' changes which involve the overthrow of whole systems of concepts are more difficult to understand (p.6). Thagard models cognitive structure in the form of a network of concepts ("mental structures representing what words represent") connected by propositions ("mental structures representing what sentences represent", p.21), with the concepts making up the nodes of the network (p.30). The networks are primarily structured via kind-hierarchies and part-hierarchies" (p.7, see appendix 9, §A9.2). In such a model conceptual change is easily represented as adding or removing nodes and links (p.32), although these changes may be more or less severe depending at what level in hierarchy the change is made (p.34).

Thagard's analysis of historical case studies suggests a range of criteria are used to determine the explanatory coherence of a hypothesis" (p.63), and that alternative explanations 'compete' on such dimensions as,

- How much does the hypothesis explain?
- Are its explanations economical?
- Is the hypothesis similar to ones that explain similar phenomena?
- Is there an explanation of why the hypothesis might be true?

(It will be noted that these factors are similar to those identified by Strike and Posner, see §2.10.4). The first of these criteria - "the explanatory breadth of the new theory" - seemed to be the most important factor (p.248). However, greater familiarity with the existing theory and its potential applications may act as a barrier (c.f. SUBSTANTIVE LEARNING IMPEDIMENTS, §1.5.3). Thagard points out that it takes time and mental effort to explore the new ideas. This exploration may include debate with peers, and reflection on the discussion (1992, p.59, c.f. the discussion above of the validity of Solomon's claims about the nature of classroom discourse in science lessons, §2.8.3).

An important aspect of Thagard's model is his acknowledgement that during major conceptual change "the new conceptual system does not arise by piecemeal modification of the old one" but "rather, the new one must be ***built up largely on its own***, and its replacement of the old is the result of a a global judgment of explanatory coherence" (Thagard, 1992, p.60, my emphasis). Thagard's model thus explains the epistemology of conceptual revolutions in terms of the *construction* of representations of ***alternative theories*** in a conceptual network (see appendix 9, §A9.6, c.f. discussion of 'multiple frameworks' above, §2.9).

Rowell and Dawson (1985) have suggested an approach to bringing about conceptual change in the classroom based on similar ideas. They suggest that once learners' basic ideas about a topic are elicited, they should be used to build the appropriate CURRICULUM SCIENCE model (scaffolded by the teacher). Once the learners have constructed the new model they are given the opportunity to practice applying it. Then (once it is familiar, and considered their own construction) the class are asked to compare the new model with specific existing conceptions, and again the teacher structures the discussion to bring out the advantages of the curriculum science idea.

§2.11: The assumptions made in the present research.

The literature reviewed in this chapter provides a theoretical base for the assumptions built into the present research. In view of the disparate views about the nature of learners' alternative ideas in science (§2.3.1, §2.3.9, §2.4, §2.5, §2.6, §2.7), and in view of the principles of 'grounded theory' work (§4.4) I have attempted to keep those assumptions as open-ended as possible so that my data analysis was not heavily handicapped by my own preconceptions. However, just like my colearners, I may not be fully aware of the biases built into my own conceptual system. I was personally introduced to many of the issues reviewed in this chapter during my first year of teaching when I attended a conference on *Concept Development in the Learning of Physics*. When I set out on the present research project, some years later, I remembered having been enthused by the conference, but did not consciously recall that I had been introduced to ideas such as minitheories (Claxton, 1983), Vygotsky's notion of language as tools for constructing knowledge (Sutton, 1983), alternative frameworks (Engel and Brook, 1983; Watts, 1983c), concepts carrying metaphysical historical baggage (Roche, 1983, c.f. Bachelard's epistemological obstacles, §1.6) and the distinction between life-world and scientific knowledge (Solomon, 1983).

§2.11.1: Theoretical position taken in the research.

My position is constructivist, in the sense explained at the beginning of this chapter (§2.1.2), and in general derives from the work of the A.C.M. However, it is also a synthetic position that takes into account the criticisms of workers such as Claxton and Solomon, so that I do not assume that each of my colearners' utterances reflect stable and extensive individual alternative frameworks. Rather, the literature reviewed informs the present research in the following way:

- a learner's knowledge relating to chemical bonding ***could be*** stored in cognitive structure as a series of discrete knowledge fragments, which are perceived as having little if any relation to one another;
- development towards an *'ideal'* understanding of this concept area would involve the integration of these discrete knowledge fragments into a single coherent and self-consistent model of 'chemical bonding'.
- to the extent that the topic is highly complex, and the information available to a learner at any level is incomplete and imprecise, (and the possibility that restructuring cognitive structure may be a long-term process) it is likely that total integration of knowledge will not be achieved.
- in the absence of full and reliable information, and in the limited time

> available to students on an A level course, the *optimum* model of 'chemical bonding' in a learner's cognitive structure may well be somewhat fragmented, and separate fragments could be incompatible to some degree.

Therefore in my research into learners' understanding of chemical bonding I will look to interpret the data in such a way as to admit the following possibilities:

(i) discrete knowledge fragments, of the form of isolated conceptions;
and
(ii) concurrent separate (*i.e.* multiple) conceptual frameworks;
and
(iii) an integrated conceptual framework for understanding bonding.

That is, I will not presuppose the extent to which my colearners' understanding of chemical bonding should be modelled as an inventory of unrelated conceptions, or as one of more coherent conceptual frameworks. The degree of integration of knowledge is a *potential* indicator of the development of understanding, but this must be interpreted in terms of the information available (at the level being studied) to learners about the topic. The *extent* to which the development of a learner's understanding can be interpreted as increased integration of knowledge is an empirical question for this present research.

§2.11.2: Working terms used to discuss research results.

In view of the lack of consistent terminology in the field (see §2.4), I set out here the manner in which I will use terms. Following the principles outlined in chapter 1 (§1.4.1), in this study I assume that my colearners' knowledge was organised in cognitive structures that are not directly observable. In chapter 6-12 I will therefore not be discussing these structures themselves, but *my models* which *represent my inferences* about aspects of learners' cognitive structures.

Particular propositions made by colearners will be represented by the term '*conceptions*' (with the proviso that the conception presented is *my interpretation*, not an element of cognitive structure itself). Where a range of propositions appear to be logically based on a closely related set of propositions, I will refer to these key propositions as forming an *explanatory principle*, and the larger network of related propositions will be called a *complex*. In the final chapter, chapter 12, I will consider whether the *explanatory principles* and *complexes* presented could appropriately be described in terms such as Gestalts or conceptual frameworks.

The stability and degree of integration of my colearners' thinking about chemical bonding, and the insight this may provide into any underlying cognitive structures, are empirical issues which will be explored through the research described in this thesis. The research evidence rallied to consider these issues in chapters 7 through 11 will inform the advice offered to teachers of chemistry in chapter 12.

§2.11.3: The colearner in the context of the research.

Figure 2.4 summarises some aspects of my perspective on the present research which derives from the material presented in chapters 1 and 2.

This figure is intended to represent some of the major components of the context of the present research (and has some similarity to Osborne and Wittrock's 1983 schematic representation of their generative learning model). The central feature is the learner, the colearner in my study. In the research I observe the colearner's behaviour (⑤) and interpret this to develop my models of the learner's understanding. To do this I provide a structure - such as a set of interview questions about foci diagrams - as a context for the learner's thinking (①). As teacher-researcher I am fluid part of system as ① and ⑤ make up an ongoing discourse, and ① is an interactive response to ⑤ as much as vice versa. In this way I attempt to probe the learner's Z.P.D. (zone of proximal development, §2.2.2). My questions and foci are mediated (②) through the colearner's sensory apparatus (e.g. his eyes and ears, and those parts of the brain which filter and interpret sensory information to convert it into perceptions). The colearner then constructs responses to my questions drawing upon (③) the resources of cognitive structure. These will include both the individual components of the conceptual toolkit (§1.7.2) - which act as intermediate concepts used in developing explanations and models - and the various conceptions (propositions relating concepts). This structure of conceptions will be organised to some extent, perhaps much of it as discrete minitheories, but perhaps including coherent frameworks. These may be more or less integrated (and may include partial and multiple frameworks: see figures 2.1 and 2.2). This box on the diagram represents 'stored information' that has some sort of permanence, whereas the previous box concerned the transient thought processes through which explanations may be constructed. (Osborne and Wittrock (1983, p.493) would include networks of propositions, images, episodes and intellectual skills as components of long-term memory available to a learner.)

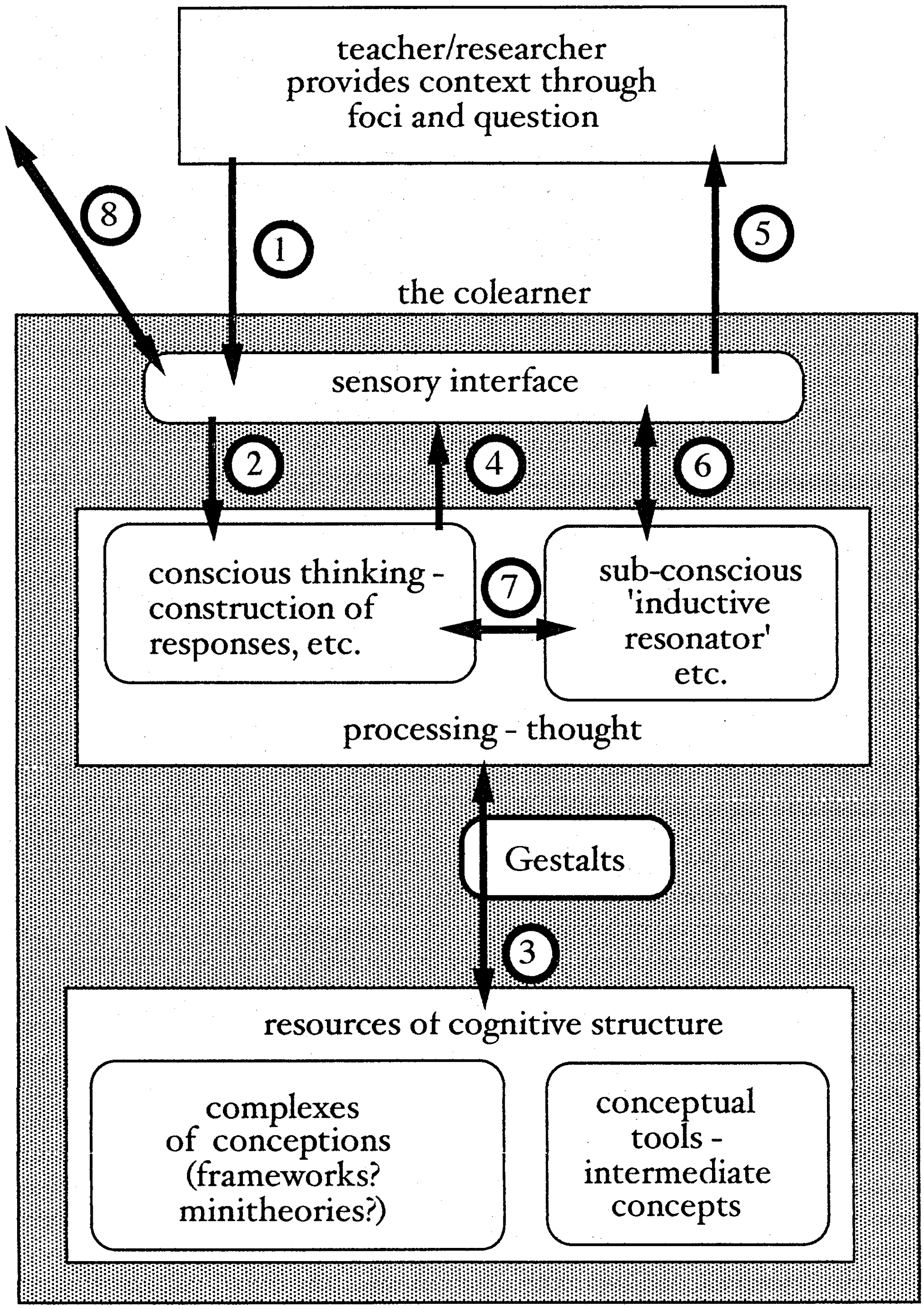


figure 2.4 - a model of the colearner in the research context

At a simple level: a question is asked (①), which is heard and made sense of by the colearner (②), who thinks about it, calling upon ideas he or she has learnt (③), and constructs a response (④) which is expressed to the researcher (⑤).

However, there are other important aspects to the system. For one thing the resources of cognitive structure are not fixed, but develop. In part they will be developed by the process of answering the researcher's questions in interviews and similar situations (so that ③ is a two way process). If the colearner has developed the metacognitive awareness to become a reflective learner then he or she will actively think about the contents of cognitive structure, and deliberately develop the resources available by searching for subsuming patterns, and looking to integrate disparate parts (c.f. §2.3.10).

There are also subconscious processes, that are not well understood but are assumed to supplement the conscious thinking that the colearner undertakes. So that some aspects of the researcher's questions (for example) may not reach conscious awareness, but may still influence conscious thinking (⑦) through other levels of processing that access some of the sensory information (⑥) filtered from conscious awareness. These subconscious processes can also feedback into the colearner's behaviour - phrasing and tone of responses perhaps - without deliberate conscious control (⑥).

At least as important are the various subconscious processes which monitor cognitive structure and process its content to develop it into a more useful set of models of the world (③). This poorly understood phenomena explains how learning goes on over months even when there is no conscious recall of material, and explains the many cases of scientific discoveries made when the scientists were not thinking about the topic, and the folk-wisdom of 'sleeping on' a problem. This particular phenomena will be discussed in chapter 4 in the context of the processes by which the researcher makes sense of qualitative data collected from learners to construct models of their understanding. In particular the means by which analytical categories are induced from data will be considered (§4.2).

A final aspect of the model is that although it is assumed that those aspects of cognitive structure which are understood as complexes of conceptions and kits of conceptual tools are open to introspection, the construction of these resources through conscious and subconscious 'thinking', and the construction of explanations etc. from them, are mediated by Gestalts which channel the thinking process without the learner being aware.

Although this model is meant to describe the system of the researcher and colearner, it must be remembered that throughout the research the colearner is interacting with peers, text books, other teachers, news media, folk-knowledge, etc. (⑧), and entering into to various other worlds of discourse apart from with the researcher. These interactions are beyond the researcher's control, and mostly occur without being observed by the researcher.

In terms of this model, the aim of the research process is to construct a representation of some of the contents of the box labelled 'resources of cognitive structure' within the researcher's own cognitive structure. As can be seen from the model this process is mediated, and thus the information distorted, by the various steps in the model (and the corresponding steps to ②, ③, ④, ⑥ and ⑦ within the researcher himself). The process is also complicated by the changing nature of the colearner's cognitive structure itself, as a result of

- the processes by which his conceptual system would be developed in the absence of new information;
- the influence of his course and interactions with various aspects of his environment; and
- the particular influence of the researcher's questions and tasks.

The development of a colearner's understanding of the focal topic (chemical bonding) will involve

- adding more tools to the conceptual toolkit;
- developing more sophisticated tools which subsume existing tools;
- learning to apply conceptual tools in a wider range of (valid) problem contexts;
- arranging conceptions into more coherent complexes;
- integrating disparate complexes of conceptions into coherent overarching schemes;

and will be demonstrated by a greater ability to answer questions in terms of the accepted models and explanations of CURRICULUM SCIENCE.

Chapter 3.

Learners' ideas about chemical bonding.

§3.0: The organisation of this review.

In this chapter the literature concerning learners' understanding of chemical bonding will be reviewed. Before turning to consider studies *directly* concerned with the bonding topic it is appropriate to consider studies into learners' understandings in a number of other topics which may be considered to relate to the 'prerequisite knowledge' that might be expected in order to make sense of the idea of chemical bonds (see appendix 5).

The relevance of these related topics, 'matter, molecules and mechanics', to an understanding of bonding will be explained, and then a brief overview of the literature relating to learners' ideas in these topics will be presented. Some of the points of particular significance for the present study will be highlighted. (A more detailed review of the literature overviewed in this section may be found in appendix 7).

§3.1: Matter, molecules, mechanics: prerequisite knowledge for understanding chemical bonding.

Although relatively little has been published about how learners understand chemical bonds, and how this understanding may develop, some of the literature relating to other science topics is relevant. The scientific concept of 'chemical bond' depends upon other assumed knowledge (see appendix 5, and also appendix 4). In particular three areas of prerequisite scientific knowledge may be identified: notions of matter and substance; the molecular model of matter; and notions of energy and force. For reasons of space the details of the literature for this section has been appended (appendix 7), and only an outline discussion is provided here.

§3.1.1: Learners' notions of matter and substance.

Scientists have a notion of 'matter', and usually classify it according to phases (i.e. most commonly solid, liquid and gas, although many substances have more than three phases). Materials may be composed of pure chemical substances, or mixtures of several such substances. For the chemist there is an important distinction between pure substances that are elements and those that are compounds. The existence of the phenomenon of *electrostatic charge* is also basic to understanding chemical bonding.

A number of studies report examples of alternative conceptions about matter (Bar and Travis, 1991; Briggs and Holding, 1986; Brook and Driver, 1989; Edwards and Mercer, 1987; Osborne and Cosgrove, 1983; Renström et al., 1990; Wightman et al., 1986; see appendix 7, §A7.1).

In particular, young children have difficulty recognising gas as substantive material. There are reports that air is only considered present when it can be felt (as when windy), and it is considered not to take up any space, nor to have any weight. Indeed sometimes air is thought to have negative weight. Youngsters may equate 'nothing' and 'just air' in an empty (sic) container. Hot air, and cold air are considered as distinct entities to one another and to normal air, and sometimes hot air is equated with heat.

There have been many alternative conceptions of state changes reported in the literature. The bubbles in boiling water have been variously identified with heat, air, oxygen, hydrogen and smoke, and the 'stuff' which leaves the water (not necessarily considered as related to the bubbles) may be seen as smoke, air, water or heat. Evaporation may be confused with boiling, but may also be thought to be a way of making milk 'thicker', or due to water passing through a surface. Water that has evaporated may be considered to cease to exist, or to become air, to spilt into hydrogen and oxygen, or to collect near ceilings. Condensation may be seen as due to oxygen and hydrogen combining, or water passing through a surface, or produced by coldness (directly, by acting with a surface, or reacting with heat). Condensation may be considered to be a distinct type of water, or even a kind of sweat. Studies also suggest that melting and dissolving may be seen as the *same* phenomenon.

For chemists the distinction between elements, compounds and mixtures is very significant, and this is another area where studies show learners have difficulties accepting the definitions, discriminations and models of science. Among the alternative conceptions of elements to be found in the literature are that they can be split up by chromatography, that they are a type of solid (and sometimes a type which releases a gas), that they can be split, that they give one product on electrolysis, that they make other elements, and that they are mixtures (but sometimes *natural* mixtures). It has also been reported that elements need oxygen to live. This is an example of animism, which will be discussed below (§3.1.4). Water is sometimes considered an element.

Compounds are thought to be mixtures by some learners, whilst others see the distinction between compounds and mixtures in terms of *how many* component elements are present. Compounds may be considered to have variable stoichiometry. Substances with more than one type of atom, such as oxides, may be seen as necessarily impure. For some learners the difference between a mixture and an impure substance is that the former is acceptable and the latter undesirable.

Although the distinction between elements, compounds and mixtures may be given in terms of molar definitions - a substance that can not be broken down into anything simpler by chemical means; a pure substance made up from more than one type of element; several types of pure substance mixed together - these are not sensible in the absence of a molecular model. (For example consider the difficulty of explaining how a pure substance can contain several elements, without using particle theory.)

§3.1.2: Learners' notions of molecules.

Scientists explain the observed behaviour of materials in terms of a well established and developed theory variously referred to in the school science curriculum as 'particle theory', 'atomic theory', or 'kinetic theory'. In a simple form this states that all chemical substances are made up from minuscule particles called molecules, and the macroscopic - or molar - behaviour of materials may be explained in terms of the properties of the microscopic - or perhaps better, sub-microscopic - molecules. It has been suggested that "the 'clumpiness' concept is, to a degree, an advance organizer for the entire field of chemical interactions" (Ault, Novak and Gowin, 1984, p.453).

Chemical bonding 'holds' the particles to one another, and so the concept of the chemical bond is meaningless without the concept of atomic-scale particles, which in turn are theoretical constructs that are only required and acquired in the context of the categories of substance and material.

Again there is much evidence in the literature that particle theory causes difficulties to learners (Ault, et al., 1984; Ben-Zvi et al., 1986; Briggs and Holding, 1986; Griffiths and Preston, 1992; Nussbaum and Novick, 1982; Renström et al, 1980; Wightman et al., 1986; see appendix 7, §A7.4).

In everyday parlance particle means a grain or drop, and many pupils appear to think in these terms, and think that molecules may be directly weighed, and seen under the microscope. It has also been shown that the whole notion of substances being comprised of particles is counter-intuitive, so that learners think in terms of the particles being *embedded* in the substance, or *being made up from* it. Sometimes the particles are thought to be infinitely divisible. Spaces between particles are often thought to be filled with the substance itself, or with other particles.

Even when learners appear to grasp the basic nature of molecules, they often apply the notions of the macroscopic world to them. This 'macro-micro' confusion means that particles such as individual molecules are often said to freeze, expand, soften, harden and so forth during phase change, so that the particles are seen as different (e.g. different weight, different size) in the different states of matter. Sometimes it may be the bonding which is said to melt. The particles may be said to individually have properties associated with the bulk substance such as conductivity, malleability, colour, odour (possibly correct!) and reactivity. The particles may be seen as 'solid' spheres, although they may also be considered as flat, or as different shapes *designed* to fit together. Other elicited possibilities are that the particles have the shape of the macroscopic object; or look like dots and circles (i.e. similar to textbook representations of atomic structures).

Sometimes learners fail to understand the basic similarity of molecules of a single substance, so that different particles may be assumed to have different sizes, shapes or weights. The *particles* in a pure substance may be assumed to contain different elements or atoms. Conversely, other pupils think that all particles in a substance must move at the same speed, or even that *all* atoms are the same size and weight.

The relationship between elements, compounds, atoms and molecules is another area of difficulty for learners, so that elements may be seen as *part of* an atom, and atoms as larger than molecules. If all the *molecules* in a substance are the same it may be identified as an element, whilst other learners report that all the *atoms* in a compound are the same.

The work of Renström, Andersson and Marton (1980) demonstrates that the acquisition of the scientific notion of molecules can be a slow process: with molecules seen variously by learners at different stages in developing their understanding of the model as only part of the substance; made up from the substance; and surrounded by the substance.

So, as Ault and co-workers propose, "the basic proposition that 'everything is made of molecules' needs the added emphasis 'and *nothing* else'" (Ault et al., 1984, p.459). This brief survey of the literature relating to learner's understanding of the molecules concept may perhaps best be summarised by a comment of Ault, Novak and Gowin,

> "The 'molecule concept' is of nearly limitless complexity. ... children have the capacity of grasping the abstract meaning of molecules at some level, though often in terms of imaginative, unconventional conceptual patterns."
> (Ault et al., 1984, p.460.)

§3.1.3: Learners' notions of force and energy.

According to physics, objects are bound together by forces, and so the chemical bond must be a force (or rather an equilibrium of forces). Later in this chapter it will be reported that learners' notions of bonding as involving force are often vague or non-existent (§3.2.2), and this is somewhat reflected in the results to be reported from the present research (see in particular chapter 10). Wightman, reflecting on the findings from her case studies on students' learning about particle theory, asks "what basis can there be for understanding bonding without previous knowledge of forces generally, forces acting at a distance, and the existence of attraction and repulsion forces?" (Wightman et al., 1986, p.268).

The literature on learners' notions in mechanics is particularly rich, and appendix 7 (§A7.7) discusses a number of studies which present learners' alternative conceptions for aspects of the *force* and *energy* concepts (Brook and Driver, 1984, 1986; Gilbert and Zylbersztajn, 1985; McCloskey, 1983; Solomon, 1992; Viennot, 1985a; Watts, 1982, 1983a, 1983b; Watts and Gilbert, 1983; Watts and Zylbersztajn, 1981).

Physics only recognises (at least in our cosmic epoch) four fundamental types of force - the strong nuclear force, the electromagnetic force, the weak force, and gravitation - so chemical bonds would be expected to be derived from one (or more) of these types of interaction. Basically the chemical bond is viewed as electrostatic in origin (i.e. deriving from the electromagnetic force).

A number of key principles from mechanics would be expected to apply to molecular interactions, including 'Newton's third law' - or Newton-3 as it will be abbreviated - that *if a body A exerts a force on a body B, then the body B exerts a force on A which is equal in magnitude, anti-parallel in direction, and acts along the same line of action.* Yet this seems counter intuitive to many learners who feel that a larger object will exert a larger force (reflected in the data presented in chapter 10). The electrostatic force between two charges can be attractive (if the charges are 'opposite') or repulsive (if they are of the same sign charge). The magnitude of this force is given by Coulomb's law, that *the force between two charged particles is directly proportional to the product of their charges, and inversely proportional to the square of their separation.* It may be noted that the force acts on both charges, and is of the same size, and must be either attractive for both particles (when it has a negative value from Coulomb's law), or repulsive for both (when positive) In these respects Coulomb's law may be seen as a case of Newton-3 (see above).

Balanced forces lead to equilibrium situations: so that a stationary system (or indeed a non-accelerating one) is either subject to no forces, or to forces that balance, and whose effect would therefore cancel (this is known as Newton's first law, or Newton-1). Where a net force acts on a body it will be accelerated as long as the force acts. Yet research into learners' notions of motion shows that this is counter-intuitive for most learners. Indeed one of the most established findings in the literature on alternative conceptions is that most people (children, adolescent students, and adults) often tend to intuitively apply an alternative notion of force and motion that is closer to the historical *impetus* theory (that a moving object's push gets used up) and are more likely to relate applied force with velocity than with acceleration.

The nature of our universe is such that balanced forces are very common as matter on a molecular scale often interacts in such a way as to give 'stable equilibria' - that is systems where moderate perturbation in either direction leads to a restoring force which returns the system to equilibrium. However this stability is not absolute, as large perturbations may lead to a resultant force between the particles that reinforces the disturbance, and the system undergoes a change in configuration to a new equilibrium. (In other words negative feedback acts on small inputs to ensure stability, but positive feedback from larger inputs ensures change is also possible.) The particular combination of fundamental constants and cosmic starting conditions that has led to a Universe with these properties - without which there would be no materials, let alone life - has been the focus of much speculation (e.g. Barrow and Tippler, 1986; Breuer, 1991 {1981}; Gale, 1981.)

The research literature suggests that learners often have difficulties identifying balanced forces: they may not distinguish force from net force, and may not pay equal heed to all forces acting in a system. Watts (1983a) has identified eight distinct alternative frameworks (n.b. ALTERNATIVE FRAMEWORKS2, c.f. §2.4.) for school children's understanding of force, and some learners may hold several of these (c.f. §2.5.2, §2.9). The single physicists' concept of force may be related to different types of phenomena to learners: something passed between bodies, something indwelling in some bodies (for example moving objects); something maintaining a status quo, etc. (§A7.7). One of Watts' frameworks for force was labelled DESIGNATED FORCES where the "force seems to reside within the objects" and is 'immanent', 'indwelling' or 'inherent' (1983a, p.222). The forces were associated with (designated to) the perceived agent causing action, so that "some objects were seen as 'having' force, others were not" (p.223). Another framework of particular relevance to the present study was that of CONFIGURATION FORCES, where learners construed an object restrained in a fixed position to "have force' (p.221). In this framework the force is seen as a *bonding* without which objects would move apart. This framework might be considered a suitable '*intermediate conception*' (§2.3.10) to CURRICULUM SCIENCE as it associates force and bonding: however this framework does identify an equilibrium situation with *a* force rather than with balanced forces.

Another related concept is that of energy. Stable configurations of systems are associated with low potential energy. Systems tend to proceed to states of lower potential energy (and in the present research this was found to be an explanatory principle that A level chemistry students do adopt, see chapter 8, §8.3.3). The term 'chemical potential energy' is sometimes used in relation to chemical systems, although this form of energy can also be conceptualised as electrostatic potential. The energy changes associated with chemical reactions are seen by chemists as very significant. The free energy change of a process is seen as a measure of its tendency to occur, and consequently knowledge of the energy changes involved in the 'steps' of the reaction allow predictions to be made about viable chemical reactions. (For the purpose of analysis the reaction process is divided into a series of steps which may relate sequentially to the hypothesised mechanism the molecules undergo, but is unlikely to correspond to discrete processes at the bench - if only because the different molecules will not be passing through the steps at the same time.) The energy involved in breaking specific bonds is calculated (although quoted per mole), along with ionisation energies, electron affinities, lattice energies, solvation energies etc.

The research literature shows that, as with force, learners' notions of energy may be very different from a physicist's. To learners, energy may be intimately tied to movement, or to vitality, or to food or good health.

The concepts of force and energy are fundamental in physics, and may be understood at various levels of sophistication. However Ault, Novak and Gowin have made the point that 'energy' and 'force' must be considered as "high level" concepts when integrated into molecular-level explanations (1984, p.452). In contrast the research literature shows that learners may have a variety of alternative conceptions for force and energy, and that indeed for many school pupils concepts that physicists consider to be distinct (energy, force, momentum, power, speed, strength, velocity, work, etc.) are either not distinguished, or are not discriminated between through the same lines of demarcation.

§3.1.4: Learners' animistic and anthropomorphic references.

Piaget (§2.2.1) had noted how children imbue inanimate objects with characteristics of living things (1973 {1929}, see §A7.6 for a brief discussion). The literature on children's understanding of particle theories provides a number of examples of animistic and anthropomorphic references to atoms and molecules (Driver, 1983; Wightman, et al., 1986; §A7.6). Anthropomorphic language has also been found in learners' notions of macroscopic phenomena (Viennot, 1985a; Watts, 1982, 1983a, 1983b; Watts and Zylbersztajn, 1981) so that objects may be said to *try* to overcome gravity, or to *need* energy (§A7.7.7).

As well as direct comments that atoms are alive, particles have been said to jump, reproduce, move anywhere they *want*, and hold hands. Thermal expansion has been explained in terms of particles and substances getting away from the heat, *liking* being cool, *needing* more room, or not *wanting* to be too close together.

§3.1.5: Scientists' animistic and anthropomorphic references.

Anthropomorphic and animistic language may be used in a quite explicit way in science, as when Millikan referred to an oil drop having an electron "sitting on its back", or by virtue of using words such as 'want' and 'need' which we associate with human desires. When Robert Boyle referred to two slabs of marble falling apart in a vacuum "wanting that pressure of air, that had formerly held them together" he presumably did not literally intend to suggest that minerals had preferences, any more than Millikan meant to imply that electrons can literally sit down, or that an oil drop has a backbone (both quotations are taken from Wolpert, 1992; p.96 and p.95 respectively). These examples are historical, but Wolpert himself refers to cells in the developing embryo which "make the decision to become a humerus" (p.137), and in another recent 'popular science' book - with the anthropomorphic title of 'Taming the Atom' - von Baeyer refers to "the intimate act of molecular mating" (1992, p.121).

It is in a metaphorical sense that the learner's knowledge has *foundations* and *scaffolding* (c.f. §2.1.2, §2.2.2). When Darwin presented natural selection in anthropomorphic language he was not suggesting that nature is alive in the same sense as an individual ape: it was an extended metaphor, and he believed that "everyone knows what is meant and is implied by such metaphorical expressions" (quoted in Beer, 1986). Similarly Lovelock's Gaia (1979) is an organism in a metaphorical sense: it is by definition supra-organismic. When Rose refers to bacteria collecting near a source of glucose behaving as if they knew the glucose was there, he believes this analogy will communicate his meaning effectively (1992, p.164). The philosopher and chemist Polanyi once commented that "our conception of science should not be one which strives at the logically impossible, self-destructive ideal of completely explicit statements" (Kirschenbaum and Henderson, 1990).

It should be noted that, as Benfey (1982) has pointed out, there is a historical tradition of 'organicist' concepts in chemistry. Benfey has suggested that one may consider molecules in terms of their biographies,

> "entities with a *life-history*, from their *birth* when they *adopt* the structure that determines their identity, through their life span with all the buffeting they receive which rotates, vibrates, stretches, bends and excites [sic] them, to their final farewell when they are fragmented, substituted, absorbed, or metamorphosed to enter the life history of another chemical species. Here we are very close to the language commonly used in the description of organisms."
> Benfey, 1982, p.397.

Benfey was explicitly using this language metaphorically. Schrödinger himself once asked "do electrons think?" (Moore, 1989, p.448). For him it was a rhetorical question, the idea was ridiculous and showed (in his view) the inadequacies of the Copenhagen interpretation of quantum mechanics, whereas it is not clear that this is the case when school pupils and students make such references (see §11.3.3 for a discussion of the extent of learners' awareness of their anthropomorphic language in the present study).

It has been argued that anthropomorphic and animistic thinking can be very valuable in increasing the appeal of school science, especially amongst girls and young women (Watts and Bentley, 1994). It is well established that in general boys and girls already have different science interests on entering secondary education (e.g. Taber, 1991) and gender-related attitudes to science are believed to be at least partially to do with different preferred modes of relating to the world (see Smail's analysis of 'characteristics of children and science education', 1987, p.83). The under-representation of women in science is a serious matter, and anything that can be done to make science curricula better match the interests, cognitive styles, and aspirations of females is to be encouraged, even if it means challenging the 'masculine' nature of science as it is normally practised (Bentley and Watts, 1987). Watts and Bentley (1994), working from a constructivist perspective, have discussed the merits of anthropomorphic and animistic language in humanising and feminising school science. The possible value of anthropomorphic language to students in the present study is considered in chapter 12 (§12.4.4).

§3.2: The literature on learners' ideas about chemical bonding.

> "Most students enter their first chemistry course with little or no feeling for chemical phenomena at the molar level. They do not come with a set of organized observations and questions for which they desire a theoretical rationale. In addition most have no fundamental understanding of electricity and magnetism. Yet, by Chapter 2 or 3, most chemistry textbooks have launched into a theoretical explanation of chemical phenomena at the electrical level. This I think is the fundamental paradox of the modern general chemistry course: *we are basically engaged in forcing students to absorb a set of theoretical answers at the electrical level, which they do not understand, to a set of questions at the molar level, which, from their point of view, do not exist."*
> (Jensen, 1995, p.71.)

As outlined in chapter 1 (§1.1), bonding is a key topic in the study of chemistry at all levels. Considering its centrality to chemistry it is perhaps surprising that there have not been a greater number of studies into the learning of this topic. The research in the literature tends to be concerned with identifying misconceptions, rather than considering how understanding develops. One of the reasons conjectured to explain this oversight (§1.3.3) is that this topic relies on prerequisite knowledge in other science topic areas, i.e. as reviewed above (§3.1). As we have seen, and as Jensen suggests in the motto above, student understanding of prerequisite concepts may be limited.

§3.2.1: Chemical bonding.

A chemical bond is "the linkage between atoms in molecules and between molecules and ions in crystals" (Penguin Dictionary of Chemistry, Sharp, 1983). Without chemical bonds there would be no condensed matter, and indeed most common gases - those that are molecular such as oxygen, nitrogen, carbon dioxide, etc. - would not exist.

In other words, from the scientific world view there is no a priori reason to expect atoms to stick together, unless there is some form of force attracting the particles together. The scientific model of the atom, as containing positive and negative charges, however leads to an expectation that atoms will be attracted together, due to electrostatic forces. In general the expectation is that there will be an equilibrium distance between two atoms where attractions and repulsions balance: at lesser distances there will be a resultant repulsion; at greater distances a resultant attraction.

From the scientific viewpoint then

- atoms would not be expected to be linked unless there is some form of physical (i.e. in terms of the laws of physics) bond;
- there are net forces between atoms which at most separations would tend to attract them together;
- this electrostatic force is the physical basis of the chemical bond.

In practice chemists do not talk of a single kind of chemical bond, but a variety of types. The most significant distinction is in terms of strength: some types of chemical bond are only disrupted at very high temperatures (e.g. in diamond), whilst others are overcome at extremely low temperatures (e.g. in neon.) This is explained in terms of the detail of atomic structure, and in particular as a result of quantum effects. Electrons in atoms occupy specific orbitals, and have quantum-mechanical spin. The orbitals are arranged in what may be simplistically seen as concentric shells, and the number and type of orbitals in each shell is limited by strict rules. The energy associated with different orbitals in the atomic system varies, and each orbital can only be occupied by up to two electrons. The atomic structure, in orbital terms, may in principle be seen to arise from a solutions to a mathematical model of the physical system (i.e. the Schrödinger equation).

When atoms interact the system then consists of several nuclei, and the configuration of all the electrons, and *in principle* the molecule or crystal, could also be calculated from the same mathematical model. *In practice* the mathematics is too difficult to solve precisely for all but the simplest systems,

> "though the newer quantum mechanics certainly had implications for chemistry, the compositional and structural aspects of the electrical revolution [in chemistry], which had already emerged in the two decades before the advent of matrix mechanics in 1925 and wave mechanics in 1926, had far more impact for the average chemist"
> (Jensen, 1995, p.89)

However various approximations are possible, and qualitative arguments based on the overlap of the atomic orbitals often give satisfactory predictions for many cases. These rules are used to explain the basis of the periodic table, and give different atoms different valencies - the number of strong bonds formed - and lead to the different bond properties perceived. So on this model:

- the numbers of (strong) bonds formed by an atom - and therefore the stoichiometry of stable molecules - is determined by physical

principles of electrostatics and quantum theory;
- the varying nature of the bonds in different substances may also be explained.

In practice chemists use a range of intermediate level concepts and rules to 'explain' bonding ideas (see chapter 1, §1.7, and the analysis of the chemistry student's ***conceptual toolbox*** in appendix 4). An example would be ***electronegativity***. Differences in electronegativity 'explain' bond polarity. As electronegativity itself may be explained in terms of electrostatics, this concept may be seen as analogous to a 'sub-routine', or a mathematical theorem, that once proved may be taken as given, and used without repeating the derivation each time. In studies to age 16, bond polarity tends to be ignored, and covalent and ionic bonds are taught as apparently distinct phenomena. In post-16 courses, such as the G.C.E. Advanced level chemistry course followed by the colearners in this study, the notion of bond polarity (and therefore electronegativity) becomes of major importance. As Lewis and Waddling have suggested "the key concepts at this level, in a study of group and period trends, are those of polarisation and ***mixed linkage***" (1986, p.22).

Other examples of this 'sub-routine' approach would include categories of bond, such as hydrogen bonds. The hydrogen bond concept may be understood in terms of electrostatics and quantum-mechanics; but in practice chemists have criteria for the hydrogen bond (e.g. the system must include a hydrogen atom bonded to an electronegative atom), and a range of phenomena that they associate with it (e.g. higher than otherwise expected boiling temperature), so that they can operate with the concept without keep relating it back to first principles.

In this sense many of the concepts applied in chemistry are used heuristically. A particularly important example in the context of the present study is the octet rule, which was ***known*** by chemists well before it was ***understood*** in terms of quantum mechanics. It is a rule of thumb that can often be successfully used to predict stable molecular stoichiometries, and charges on many common ions (*e.g.* the chloride ion will be Cl^-, where the magnesium ion will be Mg^{2+}). However, it is a limited rule. For example carbon monoxide does not match the rule, and nor does the sulphate ion, to give two common chemical species. The significance of this rule to the present research will be demonstrated in chapter 11.

§3.2.2: Bonding as the result of physical forces.

Griffiths and Preston asked grade-12 students (16-18 years) to sketch molecules of ice. They report that typical diagrams showed the molecules touching each other without spaces between, and they conjectured for these learners the concept of bonding might have little to do with forces of attraction (1992, p.620). For some students in their sample molecules were not bound due to inherent interactions between atoms, but were held together by "something external to the molecules".

In a French study of first year undergraduate science students Cros et al. (1986), looked at two topics, acids and bases (which is not considered here) and the atom. The research had three stages: 40 unstructured interviews; 50 semi-structured interviews; and then 400 students at two Universities were surveyed by questionnaires before starting their lecture courses. (So although University students, these learners were at an equivalent stage of their scientific education as the colearners in the present study at the *end* of their A level course.) Cros and coworkers found that the interactions between atoms in molecules were often unknown (38%) or poorly known (18%) (pp.308-309), and that often students were not even aware that such interactions existed (p.311). It would seem that some students did not perceive the need for physical forces to hold the atoms and molecules together. So although most students could name the constituents of an atom (p.311), 21% of the students thought there were no interactions between the components of the atomic nucleus (and a further 40% did not respond to this item - so that the majority of students were not able to suggest any type of interaction). A follow-up study found that after one year of University study the electrostatic model was better understood (Cros et al., 1988, p.332), although 16% still thought there were no interactions between nucleons, with 31% not responding to this item (p.332).

Wightman undertook two case studies with classes of 13-14 year old being taught about particle theory. Bonding ideas were referred to when an explanation of the different states of matter was needed. In one of the case study classes one of the students had transferred from another school where he had apparently previously undertaken some work on atomic structure and bonding, although he had found it "a bit difficult to believe". His recall of the details was hazy. He had covered,

> "what it's been made up out of, like the protons and neutrons and electrons and things and er, the way that they're joined together, and the electrons help to form, one electron'll go to the other two and - - them both, kind of."
> ('Eric', quoted in Wightman et al., 1986, p.107.)

Another student interviewed envisaged the forces between particles to be like elastic,

> "it seems to me that there's a sort of force banging the particles together and this can be er stretched a bit, like - if it's a solid it's a lot stronger force, and if it's a liquid it's not as strong and you can stretch it more. ... [The force is] binding the particles together ... sort of like, there's elastic holding them together and it can stretch and contract to pull the particles back together again."
> ('Guy', quoted in Wightman et al., p.106.)

Although this student recognises the role of forces, he seems to envisage the force itself to be material, something that can be stretched. Guy was still able to operate with this theory, and later he is reported as using his ideas to explain what happens when butter is left out of the 'fridge', when "the bonds between [the particles] ... aren't as strong, and so it makes it softer" (p.159).

In the case study class a group of pupils had brain-stormed their own model of chemical bonding before the teacher had formally introduced particle ideas. This model included electrostatic notions, but augmented by material linkage. As 'Suzanne' explained,

> "we were thinking that some [of the 'atoms'] were positive and some were negative. ... we did a little drawing. Say that all the positive ones had little holes in them all the way round - all the negative ones had things sticking out of them - and when they're solids they were linked together - the things sticking out went in the holes - and they came out when they were in a liquid."
> (Wightman et al., 1986, p.198.)

The teacher in this case study used the analogy of magnetism to help the pupils understand why atoms should stick together (although pointing out that the force was actually more like static electricity, a topic that had not yet been covered, p.214). Two of the pupils had difficulty with this explanation (pp.214-6): one could not understand why the atoms should separate in gases, and another wanted to know why the "magnetification" did not cause the 'atoms' in a gas to "stick together" when they collided. The teacher in the case study was reduced to sidestepping the issue as "something to do with chemistry" (p.216). Clearly understanding bonding as a physical force is an insufficient concept unless it is accompanied by some idea of how energy and force are related (see earlier in this chapter for a review of student ideas in these areas, §3.1.3). As Brook has pointed out in a review, when senior secondary pupils were asked about the behaviour of particles in a block of ice, as its temperature rose, very few referred to bonding. Even where pupils did refer to the forces between the particles, *and* the motion of the particles they did not relate the two (1986, p.36). In view of Ault et al.'s point (reported above in §3.1.3) that 'energy' and 'force' must be considered as "high level" concepts when integrated into molecular-level explanations (1984, p.452), it is not surprising that,

> "there was no evidence that any students were thinking in terms of a 'potential well', from which particles could escape if energy was supplied to them."
> (Brook, 1986, p.36.)

When a group of the students in Wightman's case study were later asked about how they imagined the bonding, one still suggested a material link - "like string between the atoms sort of holding it all together" (p.291). Others remembered the teacher's explanation and suggested "magnetism. Some sort of force", "static electricity or something like that" (p.291), but the apparently selective nature of the bonding was still problematic,

> "I suppose if it was hot, then it wasn't magnetised as much or something, and then when it was cold it magnetises more."
> "When they are hot they vibrate more, so the static isn't as strong"
> "What I thought was ... when they stop vibrating it might be a liquid"
> "When they cool down, the bonding will be increased so they won't be able to move around as much."
> (student comments reported in Wightman et al., 1986, pp.291-292.)

As one of the students commented, "the point is, how do we get the bonding back?" (p.292). A resolution of sorts was reached with the suggestion that the bonding was "ever present", but had not always "got a chance to like grip, grip [the particles] ... and keep them together". It was suggested that when the particles slowed down the bonding was then able to "get to grips" with the particles as it is "a bit easier to keep slower things together" (p.292). For other students the bond remained a material entity, and one conjectured that as the bonding was "like glue" thermal expansion might be because "the bondings get thicker" (p.305).

§3.2.3: Atomic structure and the orbital concept.

One of the most important consequences of quantum mechanics in understanding chemical bonding is the introduction of the orbital concept into chemistry. The electrons in atomic systems are located in orbitals: chemical bonding may be conceptualised as due to the interaction of the atomic orbitals to form molecular orbitals at lower energy levels. (That is, the solutions to the mathematical model are *molecular orbitals* when several nuclei contribute.) In a sketchily reported study, Cervellati and Perugini (1981) asked 290 first year University students 'what an atomic orbital is' as part of a written instrument. The main categories in their analysis of responses were

- an energy level (34%);
- a portion of space (33.5%);
- a trajectory (16%);
- a mathematical function (3%).

(The percentages are of those answering: just over 30% of the sample did not respond to this question.) In a small scale study of Advanced level physics students in three schools in England Mashhadi found that about a quarter of his sample held a 'mechanistic' conception of the atom with "fast moving electrons in definite orbits, similar in some ways to the planetary model of the atom" (1994, p.6). Just less than a quarter of the sample demonstrated a 'random motion' picture, that is, "involving random movement *within* a bounded region or *at* different energy orbits: e.g. an electron "moves randomly but in the shape of a certain shell" (p.7).

Of these perspectives, the notion of a trajectory is the least appropriate as it refers to a model of the electron in an atom (following a specific path) that has largely been superseded in advanced work. However, Cros and coworkers, found "in [fresher University] students' minds the dominant model of the atom is that of Bohr" (Cros et al., 1986, p.308). In their follow-up study after one year of University work this model was said to have receded somewhat, but without students having acquired a clear understanding of the interactions within an atom (Cros et al., 1988, p.332). They concluded that although the students had followed courses involving extensive study of the Bohr and Schrödinger models of the atom there had been very little change in their ideas (p.333). Cros and coworkers concluded from interviews that "the persistence of the Bohr model is remarkable even to the point where the answer to a question on the atom is given by a circular motion of the hand, showing the planetary system, before any word is spoken!" (p.333).

Each of the other three Cervellati and Perugini answer categories has some merit. The Penguin Dictionary of Chemistry defines orbital as a term "loosely used to describe the geometrical figure which describes the most probable location of an electron. More accurately an allowed energy level for electrons" (Sharp, 1983, p.288). This would suggest the first of Cervellati and Perugini's four options is the most precise.

However the Hutchinson Dictionary of Science defines the term as the "region around the nucleus of an atom (or, in a molecule, around several nuclei) in which an electron is most likely to be found" (Lafferty and Rowe, 1994, p.421) and the Penguin Dictionary of Science defines *orbital* as, "the space containing all the points in an atom or molecule at which the wave function of an electron (two electrons may be present if they have opposite spins) has an appreciable magnitude" (Uvarov, et al., 1979, p.298), which would suggest the second option is closer to the scientific meaning.

Chambers Science and Technology Dictionary offers the following entry for 'orbital', which is consistent with this approach,

> "The properties of each electron in a many-electron atom may be reasonably described by its response to the potential due to the nucleus and to the other electrons. The wave function, which expresses *the probability of finding the electron in a region*, is specified by a set of four quantum numbers and defines the orbital of the electron. The state of the many-electron atom is given by defining the orbitals of all the electrons subject to the Pauli exclusion principle."
> (Walker, 1991, p.632, italics added.)

Then again, the Penguin Dictionary of Physics defines atomic orbital as "an allowed wave function of an electron in an atom obtained by a solution of Schrödinger's wave equation" (Pitt, 1977, p.30), i.e. as a mathematical function. It is clear from the various dictionary definitions presented, that deciding whether learners' definitions of chemical concepts are appropriate is not always straightforward. Such lack of consensus over definitions reflects Kuhn's observation that in science "definitions were seldom taught, and [the] occasional attempts to produce them often evoked pronounced disagreements" (1977, p.xix).

Jones has argued that the failure to attempt to teach quantum mechanics (described as "the most successful tool ever invented for understanding nature") in some form from early in the science curriculum means that by the time students are introduced to quantum theory they are already so familiar with classical mechanics that they develop "an uneasy hybrid" of the two perspectives (1991, p.93). Jones suggests that this leads to "half-baked and incorrect conceptual models which stunt understanding and the development of interest" (p.93). Students' familiarity with classical mechanics, and the usual approach of introducing quantum theory through the models of the first two decades of the century (when the scientists themselves were trying to move beyond their classical notions) acts - in the typology introduced in chapter 1 - to an EPISTEMOLOGICAL LEARNING IMPEDIMENT. Shiland suggests that "the presentation of sophisticated atomic theory (quantum mechanics) in secondary chemistry texts is not accompanied by sufficient evidence or applications to promote its rational acceptance as determined by a model of conceptual change (1997, p.535). One of Mashhadi's sample of Advanced level students explained that they had been taught about electrons *as particles* from early in secondary school, and about light *as being a wave* from even earlier, and "you have a long time to think of one thing before it is even mentioned that it is possible that may not be completely true" (1991, p.8).

§3.2.4: The covalent bond.

In their French study Cros and coworkers found that although 85% of freshers knew molecules were made up from atoms, 38% were not able to suggest what the interactions between atoms might be. Only a third mentioned covalency (25%) or electron-sharing (8%) (Cros et al., 1986, pp.308-309). After one year of University science non-response to this item had dropped to 2%, and 63% were able to give an appropriate response (Cros et al., 1988, p.334).

Peterson, Treagust and Garnett describe the development and use of an instrument to diagnose grade-11 and -12 students' concepts of covalent bonding and structure after teaching had taken place (Peterson et al., 1989). Their research was carried out in South Australia, with 15-17 year olds electing to take chemistry. They developed a 15 item 'two-tier' multiple choice test - each item had two parts, the first asking student to select responses to a 'content' questions, and the second asking them to select a reason for their answer in the first part. *The covalent bonding and structure diagnostic instrument*, covered bond polarity, molecular shape, polarity of molecules, lattices, intermolecular forces and the octet rule. The topic area had been defined through a concept map and 33 propositional statements, verified by 6 'science educators'.

Peterson and coworkers initially identified relevant conceptions through "regular classroom teaching" (p.302), then carried out unstructured interviews, and asked students to prepare concept maps, and to answer open-ended written tests. 159 grade 11, and 84 grade 12, students from five schools were involved. These students had taken 6-7 months of chemistry instruction, including the topic being investigated. Peterson and coworkers concluded that "students may have acquired accurate content responses without an adequate understanding of the concepts involved" (p.308). In particular they identified thirteen 'misconceptions' (p.310). These were:-

Bond polarity:

- Equal sharing of electron pairs occurs in all covalent bonds.
- The polarity of a bond is dependent on the number of valence electrons in each atom involved in the bond.
- Ionic charge determines the polarity of the bond.

Molecular shape:

- The shape of a molecule is due to equal repulsion between the bonds.
- Bond polarity determines the shape of a molecule.
- The V-shape in a molecule of the type SCl_2 is due to repulsion between the non-bonding electron pairs [only].

Intermolecular forces:

- Intermolecular forces are the forces within a molecule.
- Strong intermolecular forces exist in a continuous covalent solid.

(The authors note that this "may be a case of mistaken terminology rather than a conceptual misunderstanding" p.311.)

- Covalent bonds are broken when a substance changes shape.

Polarity of molecules:

- Non-polar molecules [only] form when the atoms in the molecule have similar electronegativities.
- Molecules of the type OF_2 are polar as the non-bonding electrons on the oxygen form a partial negative charge.

Octet rule:

- Nitrogen atoms can share 5 electron pairs in bonding.

Lattices:

- High viscosity of some molecular solids is due to strong bonds in the continuous covalent lattice.

Peterson and coworkers concluded that "following instruction of the topic, students in this sample have not developed the appropriate conceptual understanding of covalent bonding and structure that is an integral part of the grade-11 and -12 chemistry course in South Australia." (p.312). They also comment on the use of the term "shared" to denote electrons in *polar* bonds,

> "Our supposition is that although in chemistry we can describe a "shared electron pair" to mean that the electron pair exists in some space between the atoms in a molecule, in the everyday English language "to share" means "to possess or use or endure jointly" (Pocket Oxford Dictionary, 1964, p.759)."
> (Peterson et al., 1989, p.313.)

It is notable that polar bonds seem to be taken as a sub-category of covalent bonds, rather than a class of bonds intermediate to covalent and electrovalent\ionic (see §11.6).

Two of these authors report quantitative results from the *the covalent bonding and structure diagnostic instrument* (Peterson and Treagust, 1989) based on the data from the 84 grade-12 students in the sample. Eight of the misconceptions were found to be commonly chosen by these students:

- nonpolar molecules [only] form when the atoms in the molecule have similar electronegativities (34%);
- strong intermolecular forces exist in a continuous covalent (network) solid (33%);
- bond polarity determines the shape of a molecule (27%);
- the shape of molecules is due only to the repulsion between the bonding electron pairs (25%);

- equal sharing of the electron pair occurs in all covalent bonds (23%);
- intermolecular forces are the forces within a molecule (23%);
- the shape of molecules is due only to the repulsion between the nonbonding electron pairs (22%);
- nitrogen atoms can share five electron pairs in bonding (20%).

The abstract nature of this topic area has been acknowledged by Staver and Halstead, who used a post-test to investigate 84 students' understanding of chemical bonding and geometry after instruction, in one U.S. high school (Staver and Halstead, 1985). The published report does not give details of the questions, nor consideration of the specific difficulties students may have had. The authors do conclude however that,

> "The results indicate clearly that reasoning capacity influences post-test performance as expected. Molecular geometry, shape and polarity are abstract concepts that require formal reasoning [i.e. Piagetian stage] to fully comprehend. ... Shape and geometrical concepts, however, also require spatial reasoning..."
> (Staver and Halstead, 1985, p.442)

§3.2.5: Crystal lattices.

In their study of students entering University to study science, Cros and coworkers found that crystals "remained a mystery for most" (Cros, et al., 1986, p.309). When asked about the interactions in a crystal 42% of the students did not reply, and 15% gave incorrect or completely inadequate information. Only 27% of the students referred to a clearly defined arrangement of atoms or ions" (p.309). After one year of University study the interactions within the crystal were described as "somewhat less mysterious" to the students (Cros et al. 1988, p.344) as there was some mention of ionic bonds between the constituents (19%), and an increased mention of electrostatic interactions, although only from 8% to 18%" (p.334).

§3.2.6: The ionic bond.

Butts and Smith (1987) undertook research to follow up a survey finding that *the difference in properties between ionic compounds and molecular compounds* had been rated as a difficult topic by 29% of students asked. Butts and Smith interviewed 26 high school chemistry students about this topic. They found that most of those surveyed associated sodium chloride with ionic bonding, which is appropriate, but that the students often also volunteered a description of the electron transfer event (i.e. from sodium atom to chlorine atom) which could result in the formation of the bond (Butts and Smith, p.196). In other words, it appeared that their thinking about ionic bonding was focussed on the process of ion formation, rather than the nature of the bond itself.

Ten of the students (almost 40% of this small sample) referred to *molecules* of NaCl (p.196). In the NaCl lattice each ion is bonded by electrostatic forces to six nearest neighbours (of opposite charge), and this symmetry leads to a giant ionic structure. From a CURRICULUM SCIENCE perspective it is not considered appropriate to conceptualise any discrete sub-units of the crystal lattice, above the level of the ions themselves. (The notion of the unit cell is used by crystallographers to represent the various lattice parameters economically, but this is not seen as a discrete structural unit.) The molecule concept is inappropriate in this context, as it implies a structurally significant sub-unit, such as NaCl ion pairs. It would only be meaningful to discuss the lattice structure as composed of ion pairs if the interactions *within* specific pairs differed from those *between* pairs, which is not the case in a perfectly symmetrical lattice. Four of the students interviewed actually proposed such a distinction: either that the 'NaCl molecules' had internal covalent bonds, but were ionically bonded to other molecules, or *vice versa* (p.196).

Some related conceptions were uncovered when the students were shown 'ball and stick' models. In such a model each ion is represented by a ball, and is attached to each of its six counter-ion neighbours by a wire, which could be seen to represent the electrostatic interaction (but also functions to hold the model together). In this model, the ionic bonding is the overall effect of all the wires (electrostatic forces) linking the lattice of balls (ions). Again this was not always appreciated: one student thought that the six wires represented *one* ionic bond, and *five* "physical" bonds (p.196). Another student expected seven wires "because chlorine has seven electron in its outer shell" (p.196).

Butts and Smith reported that some of the students did not think there were ions in the solid (e.g. that "solid sodium chloride doesn't conduct because it is in separate molecule") - but that the ions were formed on dissolving. Two of the students believed that dissociation only occurred if electricity was applied (p.196).

In chapter 11 results from the present research will be presented which reflect some aspects of this literature: the close association between ion formation and bonding (§11.2.2); the number of bonds being limited by valency (§11.5); and reference to ionic molecules (§11.4.3).

§3.2.7: Intermolecular bonding.

Three of the students interviewed by Butts and Smith did not appreciate the nature of a molecular solid, where discrete molecules are held in lattice positions by intermolecular forces, which are weaker than the intramolecular bonding. These students thought a grain of sugar was a single molecule (c.f.§3.1.2), and had a giant structure like diamond (Butts and Smith, 1987, p.196).

In their study of Canadian students (at 'sixth form' level) Griffiths and Preston reported that some thought that the molecules in ice were not bonded in any particular pattern (Griffiths and Preston, 1992).

§3.2.8: Bond energy.

Bond formation is an exothermic (energy-releasing) process, and bond breaking is endothermic. Indeed the 'driving force' for chemical processes is often said to be the free energy change (which must be negative for a feasible process), and bond enthalpies are often the major contributor. The greater the bond enthalpy, the more energy required to 'break' the bond, and the greater is said to be the 'bond strength'.

Hapkiewicz (1991) has commented on two common 'misconceptions' found in high school students (her evidence is a combination of the anecdotal, and a consideration of text-book treatments). The main focus of her article is the notion of 'energy rich' bonds. This is usually met in biology when the function of ATP in metabolism is considered. The conversion of ATP to ADP is used to provide the cell with an energy source: and thus the broken bond is often referred to as an 'energy rich phosphate bond', which implies that energy is released on bond fission. As Holman (1986) comments "confusion is reflected in, and compounded by, the tendency one still sometimes meets to describe ATP as containing a ***high energy bond***" (p.49). In fact energy is required to break this bond (as indeed any bond), and the misconception may arise from not considering the ***net*** effect of all the bond fission and bond formation steps that are part of the chemical reaction.

Hapkiewicz also notes that students may believe double bonds are easier to break than single bonds. This notion arises from the higher reactivity of many organic compounds with double bonds - for example alkenes readily undergo addition reactions. The difficulty here is that the double bond need to be understood as comprised as two components: the sigma (σ) bond, and the pi (π) bond. The pi bond is relatively readily disrupted, and addition reactions involve electrophilic 'attack' at this site. However the sigma bond is not broken during these reactions. The bond enthalpy for the double bond would refer to the fission of both components, and is therefore greater than for a single bond - although not usually twice as large.

§3.2.9: Bond formation and chemical change.

Chemical processes - 'reactions' - involve the reorganisation of systems of atomic cores (i.e., a core being the nucleus plus inner electrons) and valence electrons. In other words, reactions involve changes in bonds. Understanding of chemical bonds is therefore closely related to an understanding of chemical change - and the explanations given for why reactions occur.

Some previous research has suggested that learners may have alternative conceptions regarding chemical change. Pfundt found that in a sample of thirty 8 - 13 years olds substances involved in chemical processes were commonly considered either to retain their identity, although changing their properties, or to be destroyed (reported in Briggs and Holding, 1986, p.7). This compares with a scientific view that reacting substances are changed into different substances, but the matter from which they are comprised is conserved.

This scientific perspective is based on conceptualising substances in terms of molecular particles, that in turn are made up from smaller units. The substance is defined by the molecules it is comprised of. As the molecules are changed in chemical processes, new substances are produced. Conservation occurs at the level of the molecular sub-units: these retain their integrity, but reorganise into new configurations. It is *conventional* to consider the conserved units to be the atoms, although this is not strictly correct (§12.4.5, §12.5).

Clearly, although scientists have a powerful model for explaining chemical change in terms of conserved entities, it is an abstract scheme. Learners who have not mastered the particle model of matter could not be expected to appreciate the scientific meaning of 'pure substance', nor understand what it is that changes ('is destroyed'), and what retains its integrity ('its identity') during chemical reactions. Pfundt's findings are therefore not surprising if the appropriate theoretical constructs (such as those discussed earlier in this chapter, §3.1) are not available to learners.

Briggs and Holding (1986) analysed a sample of responses to an A.P.U. (Assessment of Performance Unit) survey item on chemical change. 15 year olds were given a description and diagrams to show what happened when some material was heated in a test tube. The students were asked to give observations that supported a view that a chemical change had taken place. The information given showed that after heating (and allowing to cool) the contents of the test tube had changed in four ways: an increase in volume, a decrease in mass, a change in colour, and the the material no longer appeared granular. Of 277 scripts examined, 45% gave only observations, and 41% related these to ideas about chemical change (although it should be noted only observations were specifically requested in the question). Of these, more of the responses were categorised as giving alternative ideas than accepted (scientific) ideas (23%, c.f. 18%, p.60). Alternative, or ambiguous, notions included:

- a change of state was presented as evidence of *chemical* change by "one in ten of all responses" (p.63).
- the substance had "disolved" [sic] (p.64) - although it was not clear what the solvent might be. Again a physical change is suggested as evidence of a chemical process. Briggs and Holding found the notion of dissolving was also used to describe the reaction of zinc and sulphur in responses to another A.P.U. question (pp.76-77.)
- the amount of chemical increased, there was more of the chemical after heating (p.64.) This probably refers to volume, whereas chemists would consider amount of a substance in moles, or in terms of mass. A change in density is interpreted by respondents as more chemical.
- the particles [granules?] had broken up and made more (p.64). This almost seems a magical explanation. (The same respondent went on to refer to "the juice of the orange" rising up the tube, perhaps misinterpreting what was meant by *an orange chemical* (p.59) in the question.
- the material expanded and/or changed colour due to the heat (p.65), i.e., again a physical change was envisaged - although this should have been reversed on cooling. (It might be more correct to suggest that these respondents lack the distinction between physical and chemical changes.)
- the material was richer before heating, and weakened on expansion (p.65) - here terms (richer, weakened) *seem* to be used in some metaphorical sense, although it is not possible to be confident of such an interpretation. In response to another question one student wrote that "the sulphur is obviously a more powerful substance than zinc", and again it is unclear quite what the student meant.
- the decrease in mass was used to make the change (p.65.)

Just as learners might be expected to have difficulties with notions of substances changing in chemical reactions, it is also difficult for learners to conceptualise how and why chemical processes occur without the scientific particle model. Schollum (reported in Briggs and Holding, 1986, p.8) interviewed 11 to 18 year-olds to find out their ideas about chemical change, and found alternative conceptions which were categorised as

- the conglomerate view, in which all the reactants merely join up rather like pins to a magnet;

- the 'favourable circumstance' view: this maintains the idea that the reaction products were really hiding there all along and when conditions were right they revealed themselves;
- the 'it's magic' view, in which anything could happen once the chemicals set each other off.

§3.2.10: Consequences for the present study.

Although a number of studies relating to learners' ideas about chemical bonding have been found in the literature, the body of work discussed is limited. For one thing none of these studies have reported the results of working closely with individual learners to assess the progression of their thinking.

The literature reported is based on curricula in a number of countries. The French work reported by Cros and coworkers (1986, 1988) is of interest, although it is difficult to believe that such a small number of post A-level Chemistry students in the U.K. would refer to ionic bonding. The different curricula in the two countries would seem to emphasise the boding topic to a different extent. (In the British system however, some students entering University to study physics, or mathematics may well *not* have studied chemistry post-16; where in France the baccalauréat system ensures a common background for science students.)

The literature reveals a number of 'misconceptions' about chemical bonding, although simply listing these does not illuminate their origin, nor suggest how teachers can best avoid/overcome them. It has been pointed out that bonding is an abstract topic. Zoller reviews a number of topics that give College freshers difficulty in chemistry, including the quantum model of atom; Lewis acids and bases; and electrophiles and nucleophiles; the reactivity\stability of multiple bonds; and inductive and mesomeric effects in aromatic substitutions. These are topics which either relate directly to bonding, or are described and explained in terms of the same underlying models and principles (electrostatics, orbitals, etc.) Zoller makes the point that the difficulty of chemistry is not just due to its abstract nature, but to the range of - what I have referred to above (§1.3.1) as - concepts formed by bootstrapping one on another,

> "The relatively large number of difficulties and student misunderstandings and misconceptions in freshman chemistry are probably due to the many ***abstract, nonintuitive concepts*** which are ***not*** based on, and/or derived from, and/or interrelated logically with one another, at least not in a simple and straightforward sense. Furthermore, the lack of one common denominator or a simple integrating conceptual scheme for all these complex concepts and subconcepts, and the consequent difficulty in the use of the same approach for different cases and different systems, call for different, specifically designed teaching strategies for coping with the difficulty and misunderstanding in each case."
> (Zoller, 1990, p.1063, *italics* in original.)

I hold a similar perspective to Zoller (§1.3.1, §1.7.1), and it is this feature of chemistry that makes the exploration of learners' ideas, and how they develop, important for those hoping to illuminate the learning and teaching of chemistry.

Chapter 4.

Justifying Methodology.

§4.0: The purpose and structure of the chapter.

In educational research, unlike mature branches of the natural sciences, there is not a consensus on the research approaches and techniques that lead to acceptable work. There is no *single* 'disciplinary matrix' of the type described by Kuhn (1977, p.297) that would make 'educational researchers' a unified 'scientific community' in his sense (c.f. Gilbert and Swift's 1985 description of the constructivist program: "terminology has not been agreed upon, a common methodology not shared, ultimate aims not stated", p.682). Therefore it is appropriate that I should set out my own position as a researcher to demonstrate that:

1) I am using accepted research methodology;
2) my specific data collection and analysis techniques are congruent, and are consistent with my stated methodological position;
3) my methodology is consistent with my conceptualisation of the research field presented in the preceding chapters.

The present chapter acts therefore as a bridge between the introductory chapters, which outline my research focus and locate this in a field of enquiry, and chapter 5 which provides technical details regarding the techniques used in the research.

First the notion of disparate research paradigms, or traditions, in educational research is considered (§4.1). The significance of locating the present research within an accepted methodological position is considered in terms of problematic aspects of the research process (the origin of the researcher's conjectures, and relationship between research findings and conclusions, §4.2). The study was undertaken with a specific ethical stance, and this is explained (§4.3). The present study is then described as developing *grounded theory* (§4.4). The characteristics of grounded theory are presented and related to the present research. The selection of data collection techniques used in the study is discussed (§4.5 - §4.9). Finally some specific issues of authenticity and generalisability are considered (§4.10).

§4.1: Research paradigms in educational research.

> "The documentation of students' scientific conceptions and the way these progress is a field of work that has its roots in the ethnographic tradition with its recognition of the centrality of personal meaning and of individual and cultural differences. Yet despite this orientation, there appears to be strong messages about *apparent commonalities in students' conceptions* that may have implications for future directions of work in this field."
> (Driver, 1989, p.488, emphasis added.)

Mortimore points out that educational researchers usually have training and backgrounds in other fields (1991, p.210). Research in education takes a number of forms, which are described variously using such terms as new paradigm (Reason and Rowan, 1981), post-modernist (Jennings, 1994), critical (Carr and Kemmis, 1986), feminist (Griffiths, 1995) etc. However, probably the most well recognised division is between those studies which seek general statistically valid conclusions about some average epistemic subject - and which seek to negate the effects of individual differences and idiosyncrasies - and those studies which deliberately focus on understanding the individual. This distinction is between two clusters of approaches rather than a sharp dichotomy. So Cohen and Manion form an analysis focussed on the *subjective-objective dimension* (1989, p.9), where work at the objectivist pole follows the positivist model borrowed from the physical sciences. This positivist approach assumes that the aims, concept, methods and model of explanation employed in the natural sciences may be applied unproblematically (Carr and Kemmis, 1986, p.62; Walford, 1991b, p.2). Carr and Kemmis refer to the *natural scientific view* compared to the *interpretive view*. Hitchcock and Hughes (1989) refer to *positivistic* and *interpretative* researchers, and refer to Spradley's analogy with *petroleum engineers and explorers* (pp.15-16). Gilbert and Watts (1983) refer to the former cluster as *paradigm 1*, or the *erklären* tradition ("in which explanation is the goal", p.64) and associate it with such descriptors as 'scientific', 'experimental', and 'traditional'. By contrast the *verstehen* tradition ("in which understanding is the goal", p.64) forms the basis of their *paradigm 2* which is described in such terms as 'holistic' and 'naturalistic'. *Paradigm 1* research is *nomothetic* - concerned with general laws - and is commonly associated with quantitative research methodology, where *paradigm 2* research is *idiographic* - concerned with the individual case - and is usually associated with qualitative methods. Reynolds has described this distinction as "an intellectual either/or situation where the two oppositional groups used only one method each, a method which in both cases was supported and buttressed by a supporting ideology about the nature of social science knowledge" (1991, p.194). Hammersley claims that this can lead to "clashes among researchers with different purposes who tend to see the others as engaged in the same enterprise as themselves, but simply doing it badly" (1993b, p.xix).

§4.1.1: The nature of the present research.

The purpose of my study was to investigate the *development* of understanding, and therefore it was necessary to work with the same individuals at different stages in their courses so that I could observe any changes in their thinking (§1.8). In order to understand how students relate their knowledge about chemical bonding it was necessary to use sequences of questions that went beyond finding-out which diagrams were considered to include bonds, and which categories of chemical bond were used, but to ask 'why' each response was given until a detailed picture of the colearners' thinking - what has been described in chapter 2 as intuitive theories or alternative frameworks - emerged. As Driver points out "in order to investigate such alternative frameworks, pupils' thinking has to be probed in some detail; it is the reasons pupils give for their answers, not the answers themselves, which are important" (1983, p.26). This requirement for detailed attention to the nuances of data from individual learners locates the research in the ***idiographic*** and ***interpretative*** tradition. Indeed, Pope and Denicolo have suggested "that the very choice of intuitive theories as a focus of investigation represents an epistemological stance consistent with the qualitative-interpretative approach" (1986, p.154). The work could also be described as 'clinical', and following the interview approach used by Piaget (see §2.2.1).

Chemical bonding is an abstract topic that can be understood to varying extents, and which relies on a range of prerequisite knowledge (see the earlier discussions in chapter 1, §1.7.1, and in chapter 3). It is therefore reasonable to conjecture that a learner's ideas about chemical bonding could be confused and multifaceted. In chapter 2 a case was made for accepting that learners could have ***multiple frameworks*** for what scientists may consider a unified topic area (§2.9). In order to discuss changes in student thinking it was therefore necessary to work with students intensely so that as much as possible of the complexity and nuances of their ideas could be revealed. In effect, a case study approach was required. By definition, a case study is "the examination of an instance in action" (Walker, 1993, p.165) and is said to involve "some commitment to the study and portrayal of the idiosyncratic and the particular as legitimate in themselves" (p.166). However, it was my intention to identify any "apparent commonalities in students' conceptions" (to borrow Driver's phrase from the motto above), to attempt to devise a model of developing student understanding of chemical bonding that might have some more general applicability. (Thus the grounded theory approach, discussed below, §4.4).

Carr and Kemmis suggest that participants in what they label 'critical educational science' (§4.1.2) should be the teachers and learners themselves (1986, p.158). The present study may be seen to fit this criterion. I have undertaken research in my own institution, working with some of my own students as colearners (§4.3.2).

My research focus derives from a concern that *as a teacher* I was not helping students to develop their understanding of a curriculum topic as effectively as I would wish. My research programme then was

- to find about more about how students' learning in this topic takes place (and therefore to understand aspects of student thinking at the start of the course, and how this may change over time);
- to be able to diagnose impediments to desired learning;
- and to inform the development of strategies to improve my teaching and students' learning.

This programme may be seen as having an action research flavour. This present thesis is primarily concerned with the first part of this agenda, with constructing a model of developing student understanding of chemical bonding. In the final chapter, chapter 12, I consider the extent to which this model contributes to the programme I have set out. Action research is not tied to a specific methodology: rather it is characterised by "integrating various methods in a methodologically consistent strategy" (Altrichter, 1993, p.40). In order to develop my model, I have applied principles of 'grounded theory' (see §4.4). This has enabled me to utilise research techniques that are established and accepted within the field of constructivism in science education, and which have been considered to relate to the idiographic research tradition, yet to work *towards* a model of wide applicability.

§4.1.2: The case for critical action research.

Carr and Kemmis have questioned the dichotomy between the two traditions (*erklären* and *verstehen*) discussed above: what they describe as the apparent assumption held by "those on both sides of this intellectual divide [who] adhere to a conception of science which ensures that scientific explanation and interpretative understanding are mutually exclusive categories" (1986, p.105; see also Atkinson and Delamont, 1993, p.214; Delamont and Hamilton, 1993, p.26, p.36; Hammersley, 1993c, p.47; May, 1993, p.26; Walford, 1991b, p.2). They argue that as education is a practical activity (rather than the seeking of knowledge for its own sake as in 'pure' science), then "educational research cannot be defined by reference to the [illegible]ms appropriate to research activities concerned to resolve theoretical problems, but, instead, must operate within the framework of practical ends in terms of which educational activities are conducted" (Carr and Kemmis, 1986, p.108). According to this view, educational research is undertaken to solve an educational (i.e. practical) problem - that is the mismatch between the practitioner's theory and practice (p.112). So the purpose of educational research is seen to be to produce theory that is *grounded* in the educational practice (p.122).

Carr and Kemmis suggest a model of educational research based on 'critical theory' (pp.133), founded on Habermas's rejection of the notion that knowledge is the product of disinterested intellectual activity (p.134). Rather, this view considers that knowledge arises from the interests and needs of individuals in a particular sociohistorical context (p.134). Giddens (1985) has suggested that critical theory offers an *alternative* paradigm to those traditionallyused in the empirical-analytical sciences and the historical-hermeneutic disciplines (i.e. *paradigm 1* and *paradigm 2* respectively).

Car and Kemmis argue that the interpretive perspective is useful but does not fully recognise the inherent limitations of any specific research context (1986, p.135). The critical approach attempts to overcome this disadvantage by making these contingent conditions explicit (p.137), allowing what Habermas called 'ideal-speech situations' to develop (May, 1993, p.28). Carr and Kemmis apply this approach to the educational context by identifying a new role for educational researchers, such that the research activity is recognised - and justified - as a social and political act (p.152). From this view the participants in 'critical educational science' should be the teachers and learners themselves (p.158). Carr and Kemmis conclude their analysis by advocating *action research* as a suitable basis for a critical educational science. Stenhouse goes further than this, and proposes the ideal of "an educational science in which each classroom is a laboratory, each teacher a member of the scientific community" (1993, p.222).

Action research arises from the practitioner's professional concerns, rather than from existing established theory (Hustler et al., 1986, p.3), and - like critical theory (May, 1993, p.28) - aims to improve practice and the understanding of practice (Carr and Kemmis, 1986, p.165; Elliott, 1991, p.49), rather than to develop abstract theory. Thus Carr and Kemmis' reference to *grounded* theory (discussed further below, §4.4) where the "relevant concepts, hypotheses and problems must be *inductively developed* from the 'raw data' provided by a study of the substantive area" (p.125, my italics).

§4.2: The process of induction.

As this present research has been carried out from such a perspective, and as the notion of induction is seen as problematic, it is important to examine *how* hypotheses are inductively developed from the raw data. My discussion will take the following form:

1. that the emergence of hypotheses is not well understood, but rather occurs at a sub-conscious level that is not open to rational evaluation (also see chapter 2, figure 2.3);
2. that in natural science this is not seen as problematic as there are algorithms for testing hypotheses, so that theory should be solely judged in terms of its match with the results of reproducible controlled empirical investigations;
3. that as in educational research of the type reported here the methods most associated with natural science are neither available nor appropriate (see above, §4.1.2), then the nature of the researcher's intuitions are of more concern;
4. so it is important to be aware of the possible sources of bias that may channel the researcher's thinking,
5. and a methodology is required that ensures that hypotheses may be ***authenticated*** in terms of the data collected.

§4.2.1: The problems of induction.

In the positivist model of science derived from Bacon, an observer notices a pattern inherent in the data, and then sets about testing the hypothesised pattern by making a systematic and controlled set of observations, that is, to "interrogate nature to tabulate both the circumstances under which a phenomenon is present and also those under which it is absent" (Bynum et al., 1981, p.203). There are two aspects of this method which may be considered problematic: the process by which patterns are spotted, and the process by which they are validated against nature. The latter aspect is sometimes termed *'the problem of induction'*, and is considered below (§4.2.2). In case study work a researcher is dealing with the singular case and *the problem of induction* (which concerns general laws) does not apply (§4.2.3). However, it has been suggested that even in case study work the researcher may be considered to be looking for patterns (Freakely, 1996, pp.230-231), so the former process remains important.

Pattern spotting concerns a process that may also be labelled induction: how specific conjectures are induced in the researcher's mind. That is, the process by which patterns are recognised and categories or concepts initially emerge during analysis. This is a creative act of intuition, or imagination, which can not be justified logically, and probably depends on subconscious processes: Koestler suggests that "the particular type of mental activity which takes place in the so-called 'period of incubation' [prior to the awareness of an original insight] does not meet the criteria of articulateness and logical decency required for admission into the focal awareness of the wide-awake state" (1982 {1967}, p.361). Kuhn (1970 {1962}) has pointed out how the development of science often depends on the recognition of the significance of some *anomaly*, i.e., the interpretation of some datum as *not* being adequately explained within the existing theory. This is also an act of imagination, that takes the individual beyond the communal view "that blinds him towards truths which, once perceived by a seer, become so heartbreakingly obvious" as Koestler expressed it (1959, p.10).

There are accounts of this moment of inspiration in science, perhaps the most famous being Kekulé's description of the benzene ring structure, although - ironically - it has been suggested that Kekulé invented his stories as part of a strategy to claim priority for the structure (Noe and Bader, 1993; Bader, 1996, c.f. §2.8.2). Glaser and Strauss suggest that "everyone knows" how such insights can occur at any time, during any activity, and may 'dawn' suddenly or slowly (1967, p.251). Barbara McClintock, the Nobel prize winning geneticist, has described to her biographer how much of her scientific work depended on a kind of subconscious thinking that she labelled 'integration' (Keller, 1983, pp.102-3, p.115). This type of thinking process is not only below the level of conscious awareness, but outside of conscious control, thus Lloyd Morgan's recommendation to "saturate yourself through and through with your subject, and wait" (as quoted in Koestler, 1982 {1967}, p.363). However, in general this aspect of the scientific process has tended to be underplayed, and once a hypothesis has been subjected to rigorous scientific testing, the mysterious nature of its initial induction in the mind is ignored. Indeed, Medawar (1963) claimed that - post-hoc - the hypothesis tends to be presented *as if* logically emerging from the data that was collected whilst it was being tested; and in this sense the scientific research paper is fraudulent, "because it misrepresents the process of thought that accompanied or gave rise to the work that is described in the paper", so that "the scientific paper in its orthodox form does embody a totally mistaken conception, even a travesty, of the nature of scientific thought" (Medawar, 1963, p.228).

In my own research there were moments during the analysis of data that I became aware of hypotheses about relevant categories that seemed to describe aspects of the data (such as for Annie's meaning for 'charge', §7.2.2, and for Tajinder's notion of 'conservation of force', §8.2.5). Such a hypothesis may be judged to be *authentic* if it resonates with the data: that is if the hypothesis is found to match other parts of the data set, and is not significantly challenged by incommensurate data. In my research I referred to this process of matching, of checking hypothesised categories against data, as POST-INDUCTIVE RESONANCE It is my belief, based on my own experience of the data analysis, that to a large extent the process of POST-INDUCTIVE RESONANCE occurs at a sub-conscious level. Over a period of time, immersion in a data set leads to the sudden realisation that one has interpretations that seem to fit ('resonate with') the data, but which one has not up to that point consciously thought through. One may be able to offer a *post-hoc* reconstruction of the match between data and interpretation, but one is not able to describe the inductive process. (I originally intended to use the term 'inductive resonance', suggested by the title of a piece by the musician Robert Fripp. However, I understand that this term derives from systems theory, and is a measure of a system's capacity to hold together under stress (Fripp, personal communication, 14.3.96). As my own intended use was different to this existing technical meaning, I decided to add the prefix 'post-', as the process being considered is the resonance between an induced category and the data - which occurs after the creative process of initial category induction itself.)

§4.2.2: Induction and the methods of natural science.

Medawar's argument was that induction has at its origin nothing more than guesswork, but that the *initial origin* of a hypothesis did *not* invalidate the research which followed. Scientific theory is judged by the match of theory to observation, which is independent of the creative act of forming the initial hypothesis. Whilst Medawar thought this 'fraud' gave an unfortunate distortion to accounts of scientific work, this conventionalisation of accounts (often required by journals), did not affect the validity of the conclusions, as these depended on the controlled experimental method.

A problematic aspect of positivist science is the logical impossibility of demonstrating the truth of general statements from any finite set of particular instances: there will always be alternative (albeit perhaps less parsimonious) interpretations that are consistent with a limited data set, and there is always the possibility that the instances not studied would refute the hypothesis. This is formally known as '*the problem of induction*'. Consequently, Popper (1959 {1934}; 1989 {1963}) has discussed how in principle scientists should proceed by conjecture and refutation, and seek falsification rather than confirmation of their theories. Most natural scientists may be considered to work within a disciplinary matrix (Kuhn, 1970 {1962}) or research programme (Lakatos, 1965) where there is a theoretical core (e.g. Lakatos' *hard core*) which is generally considered secure, and which - *in* *practice*, rather than in terms of pure logic - effectively limits the range of acceptable interpretations of a data set. For example, within physics or chemistry, carrying out an experiment on a Tuesday rather than a Wednesday would not be considered a variable worth controlling or exploring, and explanations that violate certain conservation laws would not usually be entertained. All such assumptions can only be formally justified in terms of the existing theoretical framework of science, which in Popper's terms should be considered provisional.

Some commentators have accordingly taken a 'relativist' position (c.f. §2.0 and §2.3.9), often inspired by Kuhn's work on scientific revolutions (1970 {1962}), and suggested that the development of science is itself irrational, and depends more on the power of rhetoric than on logical argument. So Feyerabend has suggested that "the events, procedures and results that constitute the sciences have no common structure" (1988, p.1). Regardless of the *rationality* of science, there certainly are standards of evidence that are generally accepted in scientific fields which are tied closely to accepted methodology: in terms of experimental design, data collection techniques, acceptable instrumentation, and approved procedures for data analysis. Further, each of these aspects has to be - in principal - described in sufficient detail for work to be independently reproduced. Where work cannot be reliably replicated, such as Fleischmann and Pon's work on 'cold fusion' (Close, 1990), it is considered to be pathological science, and is not generally accepted.

§4.2.3: The criterion of authenticity in educational research.

In qualitative studies in education, such as this present thesis, neither controlled experiments, nor statistical testing are possible, and the notion of *proving* theories is not appropriate. There is no agreed canon of core theoretical ideas that must be taken as axiomatic in *all* educational research (or even within science education - see chapter 2, §2.5); there are too many variables to control to follow Bacon's methodology; and research often involves unique, sentient, feeling others, rather than reproducible inanimate samples. Consequently the present work presents a model or theory which is *supported* by evidence from the data base, but there is no suggestion that my findings have been, or are capable of being 'proved'. This model is intended to relate to a concern from my own professional practice, and to inform my - and, I would hope, other teachers' - future practice (c.f. §4.1.2).

An important distinction here is between *general* and *singular* problems (Wenham, 1987). Science is generally concerned with general problems, whereas in fields such as teaching or the *practice* of medicine (as opposed to medical *research*) the practitioners are concerned with 'diagnosing' and 'treating' individual cases. As Wenham has pointed out, the approach to singular problems (where traditional notions of induction are irrelevant) should be different to that used with general problems. In particular, in the singular case it is quite acceptable to seek *confirmatory evidence* for a hypothesis, providing such tests could conceivably falsify that hypothesis (p.50).

In the research reported here, I have attempted to describe student thinking about a topic at particular stages in their developing understanding. During an interview I would form hypotheses, and then set out to test them by asking particular questions. However once the interview was finished, that opportunity was lost. A new hypothesis that occurred to me as I read a transcript - maybe months later in the light of some subsequent interview, perhaps with another learner, or just because I had time to reflect on the data - can not be fully tested. I could still interrogate the data, but I could no longer interrogate the student at *the same* stage in their studies. Nor can my study ever be *truly* replicated, in the the sense that failure to find similar results with other learners at some time in the future would not invalidate my own findings as an account of *my* colearners' cases (although it might refute the suggestion that my model has wider application). It is often pointed out that in work of the kind presented in this thesis it is not sensible to discuss the *validity* of the findings as one would when hypotheses may be tested statistically, but rather to refer to the *authenticity* of the findings (see below, §4.10.1). In view of these very significant limitations, it is important to be explicit as possible about the process through which my findings have been obtained.

§4.2.4: Sources of bias in research.

One aspect of naïve Baconian method is that it assumes the researcher brings no bias to the data: so starting with a *tabula rasa*, the interrogation of nature will cause the pattern to be revealed. Apart from the assumptions that there *is* a pattern to be found, and that the scientist is potentially able to recognise it, such a view completely ignores both the inherent biases of any human's perceptual and cognitive systems, and the individual nature of a particular learner's (i.e. researcher's) existing cognitive structure due to prior experience (see the discussion of figure 2.4 in chapter 2). A Baconian observer with no biases would presumably not be able to operate, as faced with a necessarily limited data set, which is capable of being interpreted in myriad ways, the lack of some bias would surely prevent the selection of an initial preferred hypothesis (c.f. §2.3.4). As Furlong and Edwards explain one's theory does not only 'explain' the data, but determines what is recognised as data to be explained (1993, p.51). So for example, according to Stubbs, linguistic studies in education do not make up a paradigm, and lack coherence, as they do not deal with "a well articulated set of problems in well-defined ways, with agreed standards of solution and explanation (1993, p.63, c.f. Kuhn, 1970 {1962}). Stubbs concludes that in this field there is a "problem of how researchers can place some control on their intuitions" (p.75).

In my own research I accept that the categories that I use to interpret and classify my data can not be ***assumed*** to be inherent in the data itself (§4.2.1). When I 'recognised' some pattern in the data, this was indeed a *re*-cognition. Over the course of human evolution the perceptive-conceptual system has evolved so that the developing brain has a tendency to recognise certain types of patterns, so that - for example - there is cross cultural recognition of certain classes of objects, the 'natural kind categories' (Gelman and Markman, 1986). These categories reflect the operation of natural selection, and relate to ways of thinking that had survival value in the environment in which our ancestors operated - an environment which did not include the 'objects' of modern science such as the concept of the chemical bond (§1.5.4). A striking example of this is the development of language, where there is now strong evidence to suggest that the human infant brain is structured such that the child will learn any human language to which it is exposed at the appropriate stage of development. Although at first sight this suggests flexibility, researchers have found that despite the differences between different human languages, they all follow certain specific common patterns. As Pinker explains,

> "The universal plan underlying languages, with auxiliaries and inversion rules, nouns and verbs, subjects and objects, phrases and clauses, case and agreement, and so on, seems to suggest a commonality in the brains of speakers, because many other plans would have been just as useful." (Pinker, 1995, p.43.)

Indeed Chomsky has demonstrated that children are able to use language in accordance with subtle rules that they have not been taught (Pinker, 1995, pp.40).

Furlong and Edwards emphasise the importance of the researcher making explicit the theoretical position that guided the choices about data collection, and formed the background to the presented account (1993, p.54). My own individual biases include both my own understanding of the topic area (e.g. chemical bonding), and my knowledge of other researchers' findings from studies of student learning (i.e. my reading of the literature, as reviewed in chapter 3). From a Kuhnian perspective, I also approach the research with a wealth of expectations about the types of outcomes that might be seen as appropriate within the paradigm - e.g., the presentation of 'alternative conceptions' and 'frameworks' (i.e. my reading of the literature reviewed in chapter 2, c.f. §2.11). The critical attitude would be to assume that no amount of immersion in the data will completely cancel the various biases that I bring to the research. Despite Furlong and Edwards' advice these biases are unlikely to all be explicit in this account, because I am not necessarily consciously aware of them, and indeed they would seem 'natural' to me, i.e. what Feyerabend refers to as "natural interpretations - ideas so closely connected with observations that it needs a special effort to realize their existence" (1988, p.55, and c.f. the notion of Gestalts discussed in §2.4.4).

§4.2.5: Ensuring the authenticity of the research.

Given that any provisional interpretation that I may conjecture when working through my data is a recognition of some pattern, channelled by my own existing cognitive structure (c.f. de Bono, 1969, pp.61; see also Johnson and Gott, 1996, p.563), it is important that my interpretation is *authenticated* against the data. As the process of POST-INDUCTIVE RESONANCE - whereby certain categories are found to resonate with the data, and are brought into consciousness (§.4.2.1) - is not open to introspection, and as my findings are not open to scientific replication, it is important to ensure that

(1) my analysis of data is thorough enough to ensure the authenticity of the categories used;
(2) my presentation of findings includes sufficient detail to demonstrate this authenticity.

Pope and Denicolo (1986) emphasise the importance of being explicit about processes of data reduction and the categories used in interpreting data, and the importance of presenting detailed results (§2.4.2). In the next chapter (chapter 5) my analytical procedures are detailed, and in chapters 7 to 11 the findings summarised in chapter 6 are illustrated in detail. The analytical process described in chapter 5 follows the principles of grounded theory (discussed below, §4.4). In this approach the sub-conscious nature of the inductive process is acknowledged,

> Generating grounded theory *takes time*. It is above all a *delayed action* phenomenon. Little increments in coding, analyzing and collecting data cook and mature then to blossom later into theoretical memos. Significant theoretical realizations come with growth and maturity in the data, and much of this is outside the analyst's awareness until it happens."
> (Glaser, 1978, p.18, emphasis in original.)

§4.3: Ethical concerns in the study.

Throughout this research study I have attempted to balance my desire to collect data in a systematic and reliable manner, with a concern for a high standard of ethics. In particular this meant that I felt it was essential to respect the feelings of others who might be affected by my research.

The following principles were followed:

- to inform - and obtain consent - from colleagues;
- to ensure all students involved in the case study work volunteer their time, and feel their involvement is worthwhile;
- to ensure confidentiality of data.

§4.3.1.: Informing colleagues.

I obtained the formal approval of my department and institution. Indeed through its Staff Development programme, my College supported my registration for the Ph.D. programme. Outcomes of the research (reports, publications etc.) were circulated to various key people in the College.

I informed my colleagues teaching chemistry in the college of the research I was intending to carry out, and made sure they had no objections. The only concern was that I might be involved in an exercise which was evaluating or appraising their teaching, and I was able to give an assurance this was not the case. (It should be noted that two year A level chemistry classes in the College are seldom taught by only one lecturer during their course, and it was not possible to restrict myself to students that were only taught by myself for chemistry.) My colleagues were provided with copies of papers describing the outcomes of my research. Colleagues in other institutions who provided data for the work described in appendix 2 were sent a detailed report of the findings.

§4.3.2: Informants as colearners.

In order to attempt to avoid the potential problems of a researcher-subject relationship where power lies predominantly at one pole (mine), an attempt was made to build safeguards into my enquiry. An important part of this was my conceptualisation of the role of the students who agree to partake in the study (that is, they are considered as 'colearners' in the research).

The most important principle I set-out for my study was to respect my students' right *not* to be involved in my research unless they wanted to. This included

(a) not assuming that colearners would wish to continue their involvement, but rather inviting them to each subsequent research session;

(b) making it clear that colearners were free to leave the study at any time, and that they could decline to be involved on specific occasions;

(c) making a point of asking colearners how they felt about each research session at its end - indeed I introduced into the research a simple feedback form (see appendix 10), as well as asking verbally . One colearner who was keen to be involved in the research but found repeated completion of the feedback form to be a little tedious after a number of interviews, agreed to keep a diary of his reflections on the experience instead (see appendix 10, §A10.3).

Appendix 10 gives details of the questions used to elicit feedback from the colearners (§A10.1), and their responses. The appendix reports how there was unanimous agreement that the sessions had been worthwhile for the colearners, and near-unanimous recognition that they had learnt something through the process of being interviewed (§A10.2.3, c.f. appendix 8).

The term 'co-researcher' has been used in the literature to describe people involved in a research project. In contrast to the traditional approach (where the roles of the researcher and subject have been clearly differentiated) alternative models have been proposed where the 'subject' becomes coresearcher and the researcher becomes cosubject (e.g. Heron, 1981a,b). The term coresearcher seems appropriate when applied, say, to teachers in classroom studies, such as the teachers involved in the CLiSP case studies referred to in the previous chapters, (Brook and Driver, 1986; Wightman et al., 1986); or to the 'subjects' of studies into teaching style and behaviour - such as 'Sandra' who contributed the 'participating teacher's foreword' to a book based on the case studies of herself and a teaching colleague (Tobin et al., 1990). Although my own partners in the research enterprise were valued as people and consulted about their own roles in the enquiry, they were not "contributing to the research propositions at all stages from the working hypothesis to the research conclusions" (Heron, 1981a, p.156), so the term co-researchers was not considered appropriate.

However, I attempted to ensure that my field work did not follow the traditional pattern that has been described as the 'rape model', where "the researcher comes in, takes what he wants, and leaves when he feels like it" (Lincoln, in conversation with Beld, 1994). The term 'colearners' seems to accurately represent the relationship between myself and my partners, without over-stating the case.

My colearners are clearly mature enough to make responsible decisions. They were students in post-compulsory education, having timetables with large gaps where they were assumed to be responsible for their own use of time. Secondly I was one of their teachers, and to some extent an 'authority figure', who is involved in evaluating student progress and making decisions (for example, about progression onto year 2 of an A level course, and recommendation for examination entry). Clearly there is scope for abuse of my position - I could have behaved more favourably towards students who agreed to be involved in my research than their peers who declined.

It might also be suggested that students brought up to respect teachers - and to be deferential towards their requests - could easily find themselves spending much time in research activities, without feeling that they are in any way benefiting from the interaction. Whilst it could be argued that time spent discussing their academic work with an 'expert' can only be of benefit to a student (as it will provoke them to think about their work, and they will learn from the experience), this begs the question, as to who is in a position to make such a decision on behalf of the student? The *students* may feel they could have spent the time more usefully re-writing their notes or reading a book. The sessions could just confuse them. Some might simply feel they would *rather* spend *their* time in some other way.

My primary data collection technique has been the use of respondent interviews (§4.6.2). Powney and Watts consider research interviews as "conversational encounters to a purpose" (1987, p.vii). *My* purpose was to collect data for my research. But it could be asked *'what purpose do my colearners have, and why should they want to spend their time talking to me?'* If the answer to that question was that they were in some sense fearful of the consequences of not taking part, then any findings would be tainted by the abuse of power implied. Of course in any personal relationship the desire to please the other may be a good reason for acting in a particular way. However, for young people to give up hours of their time, and to put themselves through an 'interrogation', I felt they should be offered something more. Of course the colearners attended College to learn more about science - partly because they were intrinsically interested and partly because of their career plans: often to seek a place at University to read science-related degrees. Interview sessions could offer the students an opportunity to learn at two levels: to learn about how well they understood the work, and to learn about chemistry through the dialogue itself. It is my perception, that this was what happened in most of the interviews, and this was supported by the evaluations made by the students themselves (appendix 10, §A10.2.3). Consequently, the research sessions became mutual learning experiences. Although the partners had somewhat different learning goals, each was aware of what the other wishes to learn from the experience. There was no deception, and the purposes are certainly not inconsistent. The relationship became symbiotic: we *were* colearners in the process.

§4.3.3: Confidentiality.

As this study was largely idiographic in nature, grounded in detailed data from individual learners, it was appropriate to refer to the colearners by names when preparing case studies, and in the findings presented in later chapters. In order to offer confidentiality, each colearner was ascribed an alphabetical code, in the order in which they enrolled in the project. In producing case studies names were given using the code letter as an initial: thus A became Annie, and T became Tajinder. (Some letters were not used, such as O, and some codes were ascribed to students who provided data focussed on another science topic which is not reported here).

In the final stage of the project, when data was collected from the DIAGNOSTIC INSTRUMENTS (appendices 2 and 3), teachers sending me data were given a breakdown for their own classes, but the general report sent to all the contributing institutions did not give any details of the schools and colleges, nor of individual students or classes.

Ensuring confidentiality is not a straightforward matter. In one sense the researcher would like to give as much background information as possible to readers of a research report. However, the more information presented, the more likely it is that individuals could be identified. This issue arose in the present study. In a paper presented at a conference I included details in the appendix of dates of birth and examination grades at entry to college, of the colearners whose ideas were discussed. In addition my own affiliation - and therefore the College attended by the colearners - was given at the head of the paper. *In principle* this could have been sufficient to identify the individuals who made specific comments reported in the paper: a point brought home to me when the colearners informed me that they had been reading the paper in the College library, and had worked out which of them was represented by which code letters. The students did not criticise my inclusion of the personal data, and they pointed out that they had only achieved the identification by collectively exchanging information of their birth dates and exam. records, but I felt I had - in principle - failed in my duty to protect their identities. In the present account of my work details about individual learners are only provided where it is felt to be of specific relevance to the reader.

§4.4: The research as grounded theory.

> "A grounded theory analysis starts with data and remains close to the data. Levels of abstraction are built directly upon the data and are checked and refined by gathering further data"
> (Charmaz, 1995, p.28.)

The present research has followed the approach known as grounded theory.

§4.4.1: An overview of grounded theory.

The research reported here followed an approach that is described as 'grounded theory'. Grounded theory derives from the work of Glaser and Strauss (1967), who believe theories should be 'grounded' in the data that are generated during research (Cohen and Manion, 1989, p.141), rather than research just being determined *by* established theory. Although this approach was developed by sociologists, Glaser describes the approach as a "*general methodology*" (1978, p.164), and claims it has been used in many fields, including education (p.3). In this approach theory is generated from (Glaser and Strauss, 1967, p.31) - or is considered to emerge from (Charmaz, 1995, p.47) - the data collected. Glaser talks of developing 'theoretical sensitivity', which requires commencing the research with as "few predetermined ideas as possible" so that observations may be recorded with as little filtering through preexisting hypotheses as possible (1978, pp.2-3). Woods refers to the process of preparing to enter into research as "washing your mind clean" (quoted in Measor and Woods, 1991, p.69).

Much of what has already been presented in this thesis demonstrates the difficulty of avoiding - and even recognising - one's biases: the researcher will construe the world through his or her personal construct system (§2.2.4), and is trained within a research tradition (§4.1). However, the significant point here is that rather than commence research assuming the relevance of the theoretical concepts and categories that are established in the research field, and therefore fitting the data to those categories, the grounded theorist has a critical attitude and attempts to be led by the data itself (Glaser, 1978, p.4, see §4.4.3 below).

The research design itself also emerges during the research, as the researcher uses *theoretical sampling* (i.e. decisions about on-going data collection are guided by the emerging theory, Glaser and Strauss, 1967, pp.45), as the research becomes more focussed (see figure 4.1).

There is a constant process of reviewing the emerging model against the data collected - the 'constant comparison' method (Glaser and Strauss, 1967, pp.113-115), using 'double-back' steps (see §4.4.4 below). In other words, as new data is collected and analysed, the provisional model (and therefore the analytical scheme) is reviewed, existing data is revisited in the light of the revised analytical model, and where and how to collect data next is reconsidered. During this process there is a *gradual shift* in the *balance* of the researcher's emphasis from data collection to analysis to writing-up. The end-point is reached by a process of *theoretical saturation* where further data collection and analysis does not significantly change the model being developed (Charmaz, 1995, p.28, p.31, p.34; Glaser, 1978, p.16, p.36, p.85; Glaser and Strauss, 1967, pp.61-62; Reason and Rowan, 1981, p.xx; c.f. Johnson and Gott's notion of "developing the neutral ground" between researcher and learner "through a process of successive approximation", 1996, p.568).

Shipman (1988) has pointed out some of the shortcomings of the grounded theory approach. He suggests that it is not always easy for researchers using this approach to decide what data to collect at points in their research (p.41) - although I did not find this. Shipman also suggests that in accounts of research the evidence and interpretation can run together, making it difficult for readers to distinguish (p.63). I have attempted to aid the reader by providing examples of verbatim data extracts to support my interpretations. Shipman also suggests that reports may be unbalanced by the tendency to focus on the aspects of findings that are considered theoretically interesting (p.63). However, providing that the reader is aware of the nature of grounded theory, this could be considered a strength rather than a weakness.

In the present research the first stages of data analysis commenced as soon as data was collected, and informed the subsequent episodes of data collection (§5.2). For example, analysis of recordings of interviews led to additional questions and focal diagrams being incorporated in later interviews (§5.1.3). Some specific interpretations of interviewees' thinking also formed the basis of items used in pen-and-pencil instruments (the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT, and the TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT, see appendices 2 and 3) that were used with larger samples of learners.

§4.4.2: Data collection. The present research underwent several phases, each informed by the earlier work, and data collection and analysis were carried out concurrently. Although this research is primarily an interview study, other forms of data were also collected (§4.5) in order to,

- provide sources of contexts for interview discussions that arose from the colearners' own course-work;
- authenticate the findings of interviews against evidence of the colearners' thinking from other contexts;
- to test the categories derived from the analysis of the colearners by comparing them against data from a wider range of learners (c.f. Charmaz, 1995, p.42).

Glaser and Strauss argue that there is no single research technique that is necessarily most appropriate for generating grounded theory, and they recommend collecting different types of data to provide a range of *vantage points* for exploring categories - what they call *slices of data* (Glaser and Strauss, 1967, p.65). Labov recommends "supplementing interviews by collecting data from tests, elicitations, experiments, observations and different types of recordings" (reported in Stubbs, 1983, p.221). In the present research, interviews were supplemented by recording student dialogue, using the construct repertory test, and collecting samples of student course-work such as concept maps and tests. This eclectic methodology reflects the "openness and flexibility of approach" considered appropriate for grounded theory work (Charnaz, 1995, p.47).

The first stage of data collection consisted of an interview study for which data was collected over the period January 1991 - May 1992. A 'deck' of 17 diagrams, informed by an analysis of the topic area at Advanced (A) level, were prepared on A4 paper to act as foci for the interviews (§5.1.2). The colearners in the study were four volunteer A level chemistry students, denoted here by assumed names: Annie, Brian, Carol and Debra. The four A level chemistry students were interviewed at three stages of their A level course: these conversations were recorded on cassette audio tape. During this phase points of interest were noted, and *new foci diagrams added to the pack*. It was also decided to trial a supplementary technique based on Kelly's triads (§4.7), and another student (denoted Edward) was enrolled in the project, initially for this purpose. (Edward was the only colearner *I* did not teach for chemistry, although he was in my A level physics class).

During the second phase, September 1992 - June 1994, ten students commencing A level studies were enrolled to be interviewed. These colearners are denoted as Jagdish, Kabul, Lovesh, Mike, Noor, Paminder, Quorat, Rhea, Tajinder and Umar. Of these ten volunteers, eight provided data for the duration of the first year of the course (two left the course) and four continued to be interviewed through their second year (see appendix 1). In addition to the prepared foci diagrams, other probes were used (for example, early in the course the colearners were asked to list, and then try and draw representations of, different types of chemical bonding they were aware of.) Detailed notes of the interviews were made, including full transcriptions of large sections of tape (§5.2.1). As well as interviews, tasks based on Kelly's triads (§4.7) were used, and other data that was available to me as a teacher - such as examples of course work - were collected (§4.9). Some additional sessions were taped with colearners working as pairs on past examination questions relevant to chemical bonding (§4.8).

Throughout the period of the interview study, supplementary data that could be relevant to the research was collected from *other* learners. I will refer to this source as 'incidental data'. This took the form of keeping copies of students' responses to relevant course work activities such as induction exercises, and certain tests. Sometimes this involved an individual response that was considered potentially interesting, and sometimes copying the work of an entire class. When a substantive question about bonding was included in the A level mock examination one year, all the responses to that question were copied. This material provided a bank of data which could be interrogated to compare with the findings from the colearners interviewed.

The grounded theory approach is intended to generate models that can potentially be tested by traditional logico-deductive techniques (Charmaz, 1995, p.48) - thus grounded theory creates a bridge between idiographic and nomothetic research (§4.1). The third stage of the project was designed to test the relevance and applicability of the findings of the previous stages to the teaching of chemistry at A level. Some of the specific notions elicited in the study were used to design paper-and-pencil instruments that could be used to survey and diagnose these conceptions in wider populations.

It was not within the brief or resources of this study to undertake a large representative survey of chemistry learners: but an attempt was made to test the feasibility of such a survey for two areas (ionic bonding and ionisation energies) where the study suggested colearners could be applying common alternative conceptions. Although the case studies of individual learners are considered to be of intrinsic interest to understanding the learning of science at an individual level, the diagnostic instruments developed demonstrate that the present research uncovered notions that should be of widespread interest to the chemical education community. In order to avoid some of the criticism of multiple choice formats (see below, §4.5), these diagnostic tests presented a selection of statements, each of which could be separately judged as 'true' or 'false'. In addition a 'do not know' option was available. These instruments are discussed in appendices 2 and 3, and some of the findings obtained have been incorporated in chapters 10 and 11.

§4.4.3: Use of the literature. A more traditional approach to research would place the literature review ***before*** research design, data collection and analysis, as research questions would be derived from the existing literature. In grounded theory work it is recommended that the literature search is delayed in an attempt to avoid the researcher deriving categories from the literature rather than the data (Charmaz, 1995, p.47; Glaser, 1978, p.31). However, it is accepted that the researcher will have knowledge of the field that will influence the interpretation of data, and even that a general awareness of a wide range of possible variables and theoretical ideas can increase sensitivity to the data (Charmaz, 1995, p.32, c.f. Kuhn 1970; Furlong and Edwards, 1993, p.54; Glaser, 1978, p.3; Glaser and Strauss, 1967, p.253). Although categories from the literature might well be adopted in a grounded theory study, the researcher has to develop an ***emergent fit***: that is modify the category to fit the data and not select the data to match the category (Charmaz, 1995, p.38; Glaser, 1978, p.4).

In the present research the literature was studied alongside the processes of data collection and analysis. A provisional literature search was carried out in the Summer of 1990, when I was awarded a study visit to Merton College, Oxford. Data collection commenced in January 1991. My study of the literature continued throughout the research, but the drafting of a formal literature review for this thesis did not commence until the interview data had been collected, and much initial analysis had been completed.

§4.4.4: Analysis.

> "Grounded theory methods consist of a set of inductive strategies for analysing data. That means you start with individual cases, incidents or experiences and develop progressively more abstract conceptual categories to synthesize, to explain and to understand your data and to identify patterned relationships within it."
> (Charmaz, 1995, p.28.)

Analysis of data in grounded theory studies proceeds through a process called 'focussed coding'. In practice this means that when the researcher ***starts*** analysis, the data (for example, extracts from an interview transcript) are annotated freely with the impressions and interpretations they suggest. There is no limit to the number or format of these codes. However, as analysis proceeds the researcher begins to develop a set of codings that seem to be most pertinent in explaining the data, and over time these will be organised into a set of categories based on groupings of the codes that seem most significant (Charmaz, 1995, pp.37-40).

Two points that should be reiterated here are, firstly, that this is an inductive process (Glaser and Strauss, 1967, p.251) and therefore heavily dependent on subconscious thinking (§4.2), and that it is therefore necessary to constantly check on the authenticity of codes and categories by 'double back procedures' (§4.4.1). Figure 4.1 represents this aspect of grounded theory procedures schematically.

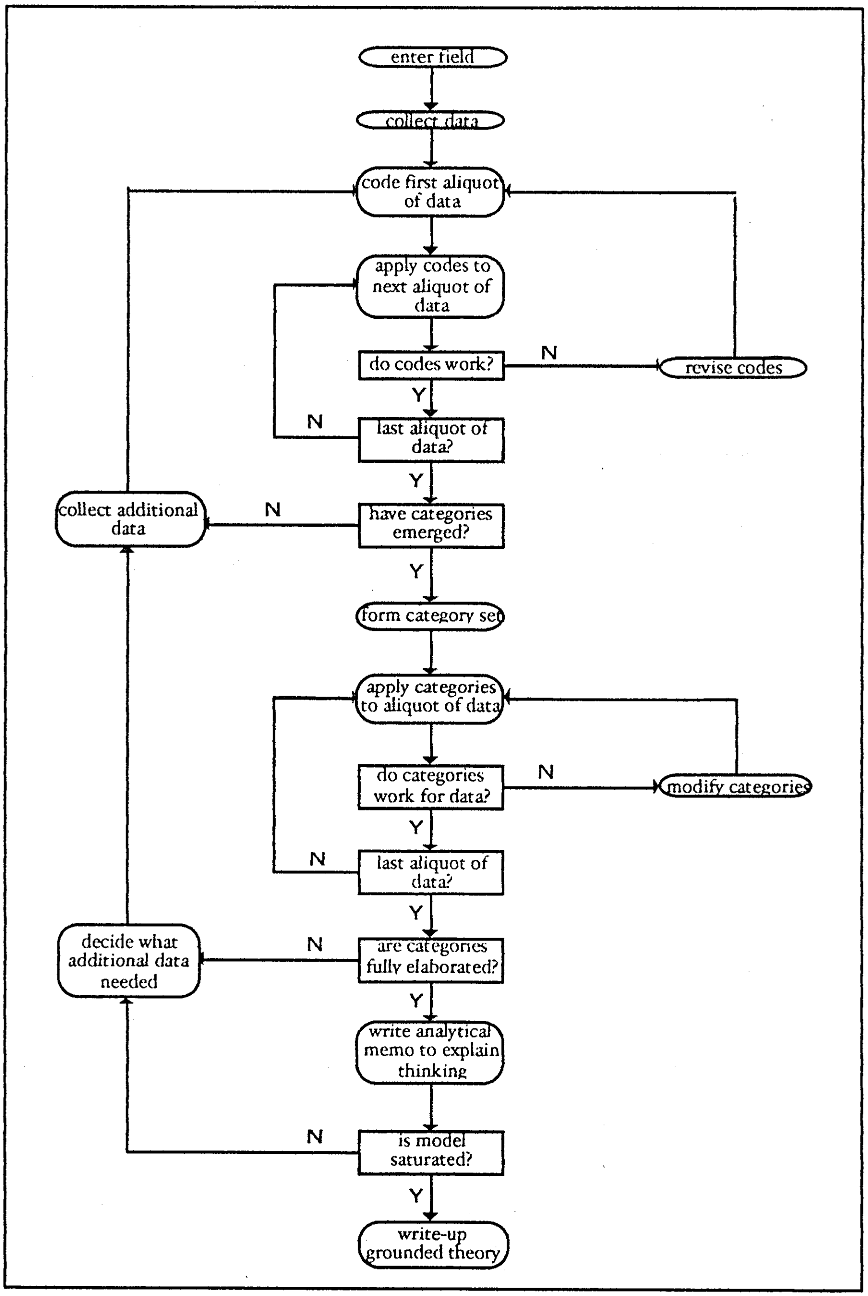


figure 4.1: a schematic showing the nature of grounded theory

Therefore the set of codes that emerge from initial data analysis may be used to work through large quantities of data - but it will be subject to additions, deletions, substitions and modifications. When categories are developed they are tested against the data already coded, as well as being used to study new data. The categories must be refitted, that is modified to match the data being studied, and gradually elaborated and refined to describe finer details of the data (Charmaz, 1995, p.42; Glaser, 1978, p.4). Theoretical sampling is then undertaken, that is data collection is targeted to inform the developing scheme (Ball, 1991, p.184; Charmaz, 1995, pp.43-46). In particular Charmaz recommends testing categorises by comparing them against data from different people, against data from the same people at different times, and against other categories (p.42). If theoretical sampling appears to collaborate the categories being used, and the relationships between them, then Charmaz would argue that they may now be considered as 'concepts' (p.45). (This process, moving from codes to categories to concepts, has a parallel in Gilbert and Watts' description of the analysis of interviews of students discussing aspects of science, when they suggest three levels of analysis: moving from conceptions to categories to frameworks: 1983, pp.69.)

The starting point for analysing the data collected in the present research was my own conceptualisation of the topic area (see chapter 1, and appendices 4 and 5), and some features of learners' thinking that seemed important in my reading of data from other studies, such as detailed data given in some of the CLiSP reports presented in the literature (e.g. Brook and Driver, 1986; Wightman et al., 1986). These sources provided some of the codes used in the initial interpretation of data.

The details of the analytical process are presented in the next chapter (§5.2), and here only a general outline will be given. The interviews from Annie, Brian, Carol and Debra were analysed by summarising the contents and coding points of interest for exploration in the subsequent interviews and analysis. The interviews were transcribed. One of the colearners, Annie, was selected, and a case study was prepared (which is described in chapter 7), largely organised in terms of my initial analysis of the topic area.

The findings from the case study were formally written up and presented to a critical audience (at a symposium at a conference of the *British Educational Research Association*); reviewed and published (in *Research in Science and Technological Education*). One outcome of this work was a shift in focus from the initial categories used to organise the work (based on the topic) to particular aspects of Annie's thinking (see in particular §7.4).

A procedure was developed for the on-going analysis of data from the second cohort of colearners, and this was formalised in a working paper (in June 1993). When the cohort had completed their studies, Tajinder - the colearner who had provided the most data - was selected as the most suitable case for detailed analysis. By this time the basis for organising the case study were features of Tajinder's own conceptualisation of chemical bonding, rather than my own initial analysis of the topic. To write this case I spent a number of months where I worked only on the data from this one learner, and refined the analysis through a number of stages (see chapter 5, §5.3). At the end of this period I wrote up the case summary (August 1995), that has since developed into chapter 8 of this thesis.

In the present research the case studies of individual learners were prepared, firstly as 'findings' in their own right (i.e., chapters 7 and 8; Taber, 1995, Taber and Watts, 1997), and as part of the process of developing the general model outlined in chapter 6, and documented in chapters 9, 10 and 11.

The data from the other colearners were re-examined in the light of the case study of Tajinder. Selective (in terms of the categories emerging from the analysis) case studies were prepared for Carol, Debra and Edward. Case studies of Jagdish and Kabul were then also produced in terms of the emerging analytical model. In this way the categories were checked against the data from a number of informants. Through this process the categories used in the analysis were refined. The next stage was to interrogate the data from other colearners (Brian, Lovesh, Mike, Noor, Paminder, Quorat, Rhea and Umar), to further refine the analytical model. Finally, the data collected from other students was considered and coded in the light of the emergent categories.

Some further interviews had also been undertaken with a number of colearners *subsequent* to Tajinder's cohort, and initial analysis of this data had been undertaken (by reviewing the recordings and producing outline protocols of the content). However, it was felt that *saturation* of the theoretical model had been achieved, and that further analysis of this data would add little to the model (§4.4.1).

§4.4.5: Reporting.

At this point the findings were written up *thematically*, to give chapters 9, 10 and 11. Charmaz has recommended that grounded theory reports should include sufficient verbatim material to allow the reader to judge how the analysis follows from the data (p.47, a similar point is made by Furlong and Edwards, 1993, p.54), and as Walker points out "case studies do not really lend themsleves to *data collapse*" (1993, p.179).

However - as Pope and Denicolo point out (1986, p.156) - the researcher faces a dilemma between two responsibilities to readers: to provide sufficient evidence to justify the model presented, and to produce a research report that is succint enough to allow a reader to appreciate the key points.

In this research I have attempted to produce an authentic account that retains readability (§5.3). In order to avoid disrputing the narrative flow of my arguments (Zeller, 1995), I have selected a limited amount of verbatum material to illustrate the main points of my model. I have however *also* appended a range of additonal extracts from the data to provide the reader with sufficient material to evaluate my analysis (see §5.3).

§4.5: Choice of research techniques.

As explained above (§4.4.2) procedures to develop grounded theory "start with individual cases" (Charmaz, 1995, p.28), and work towards models that may "be verified through traditional logico-deductive methods" (p.48). This present study was able to generate such ideas, and a limited amount of survey work has been undertaken to show the feasability of testing the generality of aspects of the model produced (appendices 2 and 3).

However, the bulk of this thesis is concerned with *constructing* a model of the development of learners' understanding about chemical bonding, which is grounded in data reflecting learners' thinking. This therefore led the selection of data collection techniques. As Driver, Leach, Millar and Scott have explained, studying learners' thinking *in depth* (in their case about the nature of science) excludes techniques designed to collect data from a wide range of learners. As in their study, the ideas being explored in this research were "subtle and complex", and the nuances of individuals' thinking were unlikely to be fully elicited by written surveys using preestablished questions, or particularly with multiple choice items forcing a choice between preselected responses (Driver, et al., 1996, p.66).

The main data collection technique used in this present study was the interview (§4.6). Interviews provide opportunities for the researcher to test the validity of interpretations by asking follow-up questions, repeating questions at a different point in the interview, and asking about the same point in a different context (c.f. §2.2.3). Interviews also provide the researcher with the flexibility to respond to the respondent's comments: to test hypotheses about their meaning and reasoning, to clarify ambiguity, to explore the degree of tentativeness of a response.

Solomon has suggested that any *single* approach to investigating students' understanding will only cue a limited range of responses from the repertoire available to the learner (Solomon, 1992, p.40). However - as Driver et al. intimate - other available methods suffer limitations. For example, in survey work, questions have often been set in a multiple-choice format (see for example the Bar and Travis {1991} data discussed in Chapter 3, §3.1.3 and appendix 7, §A7.1) based on alternative conceptions elicited in interviews. Bar and Travis report that the proportion of respondents *selecting* an explanation presented as an option in a multiple choice format may be much higher than that giving the response spontaneously in response to open-ended questions (pp.369-370). Solomon's own research group's use of this type of format has been criticised by Driver and coworkers, as

- students' choice of response is constrained by the options offered, none of which may capture precisely a students' view;
- the multiple choice approach relies heavily on students' interpretation of the wording of the question matching that intended by the researchers who framed the responses offered;
- variation of view within each answer category is obscured.

(Driver, et al., 1996, p.47.)

In the present research the approach taken was to base the study on interviews, which were considered to be the most powerful technique for exploring a learner's thinking in depth, but to use auxiliary data as a means of *methodological triangulation* (§4.10.4). It was considered that there was sufficient scope within the interview context to elicit comments that could allow a valid representation of the colearner's thinking to be built up for those aspects of thinking about the topic which could be triggered and probed during the interviews. However, to take on the concerns about context and cuing, relevant data was collected from the colearners' normal course work (§4.9). This data was scrutinised, and when points of interest were discovered they were, where possible, probed in the interview situation. In this way the advantages of the flexibility and depth of the interview situation were combined with the opportunity to bring in points from material cued in a different social context.

In addition, two supplementary methods of data collection were used. The first was Kelly's construct repertory test, which used different foci to the interviews, and had a very different 'task' structure (§4.7). The second was the setting up of dialogues between pairs of colearners (§4.8).

§4.6: Interviews.

The main technique used in this study then is the semi-structured respondent interview. There is a strong tradition of enquiry using interviews in research into learners' ideas in science (considered further below, §4.6.2).

§4.6.1: The use of interviews.

There are significant advantages to exploring learners' ideas through talk (§4.5), but it might be asked whether interview studies are the most appropriate research tool when most formal teacher-set assessments in science are written, as are terminal examinations such as A level. (Although the course followed by the colearners had a 'practical' paper, all instructions were presented in written form, and all answers had to be given in writing.) If learners were to demonstrate apparently different levels of understanding in written and spoken responses this would not invalidate interview studies *per se*, but could diminish their direct relevance to the practice of learning science in school and college.

This question has been considered by Seddon and Pedrosa who explored the hypothesis that students answers might depend upon whether the questions and answers were written or verbal (1988, p.337). They investigated the issue with first year science and engineering undergraduates in Portugal, in the context of questions about atomic and molecular structure and chemical equilibria (p.339). In their study they both compared the effects of presenting a set of questions in four modes (spoken question, spoken response; spoken question, written response; written question, spoken response; written question, written response) to different groups of students, and also of presenting students with questions divided into the four modes. Although their results demonstrated a small number of significant effects (on 8 statistical tests out of 375, at the 0.01 level) they concluded that the mode of questioning made no practical difference to student performance, and that all four modes could be considered equally valid (p.342).

Wightman, working with secondary school students, found that students' written responses did not always match their comments in interviews. In her case studies of secondary classes, Wightman clearly felt that the interview data was more reliable, and reported that her research made her question the validity of exploring children's ideas in science by considering only their written responses (Wightman et al., 1986, pp.317-318).

§4.6.2: The semi-structured nature of the interviews.

The interviews used in this study are of a type often described as "semi-structured", which allows the interviewer flexibility to devise questions in situ in response to the interviewee's comments. This approach is appropriate for *developing* a model of student understanding (§4.5) - although it would *not* be suitable for testing the generalisability of the model (as "the interviewer is more free to probe beyond the answers in a manner which would often seem prejudicial to the aims of standardization and comparability", May, 1993, p.93).

Powney and Watts (1987) suggest that the most significant classification of interviews is as either *respondent interviews* (where "the interviewer retains control ... [and] it is the interviewer's 'issues' that matter", pp.17-18) or *informant interviews* (where it is "primarily the interviewee who imposes" the agenda, p.18). In their terms my interviews would be classed in the former category. Such respondent interviews may be more or less structured, and the descriptor 'semi-structured' used above could be equated with what Powney and Watts describe as "a loosely structured interview [which] ... implies a general set of ideas to which the interviewer would like some responses at some point in the session, though the order and exact wording are not important" (Powney and Watts, 1987, pp.17-18). So I entered the interview context not with a fixed schedule of questions, but rather with specific foci (§5.1.2), and certain questions in mind (§5.1.3).

The interviews followed the general pattern of the 'interview-about-instances' approach (Osborne and Gilbert, 1980) which has been outlined as "*tape-recorded dyadic discussions with a pupil, using a series of pictures as a focus*" (Watts, Gilbert and Pope, 1982, p.11). This technique involves presenting the learner a series of diagrams which are considered to be feasibly related to the focal concept, and then asking the learner *whether* the figure is perceived as representing an example of [their version of] the concept, and *why* they think so (Osborne and Gilbert, 1980, p.376; Watts and Gilbert, 1983, pp.162-3). This approach is flexible, and used in a non-intimidating way to allow an informal discussion to develop (Watts, 1983a, p.218). It is recognised that the technique it suitable for case studies that explore the ideas and meanings of individual learners (Watts, Gilbert and Pope, 1982, p.12).

My initial interviews were based around 17 simple diagrams that I had prepared to represent chemical species and structures (see chapter 5, §5.1.2). Some minor changes to a few diagrams were made as a result of early interviews, and subjects' comments led to a considerable expansion of the 'deck' of figures (although the full set of figures was not used in any one particular interview). The two questions I used to start discussion in the early interviews were 'what do you think is represented in this figure?' and 'is there any bonding represented in this diagram?', or some paraphrasing of these (§5.1.3). Follow-up questions obviously depended on the responses the students made. In subsequent interviews with a specific subject I would have a list of questions I wished to ask, formulated on listening to the recording of the first interview. In addition interesting points from one interview could lead to ideas for probing questions with other colearners.

With the colearner whom the main case study is based - Tajinder - there were a large number of interviews (23). Some of these followed the same outline as those used with the other colearners, but some were more open-ended, and were allowed to develop into a range of topics that I considered *potentially* relevant to the theme of chemical bonding. This both allowed Tajinder to have a significant input into the 'agenda' for some of the research sessions, and broadened the *context* of the discussions.

§4.6.3: The clinical nature of the interviews.

The interviews that have been carried out for this study have been clinical in nature (§2.2.1). Although the interviews have taken place in the College the subjects attend, and the interviewer has been known to the colearners, the interview process has been formalised in a number of ways that distinguish it from the normal contexts of teacher-student talk (in classes, or informal social chat in corridors, refectory etc.)

The interviews have been by mutually agreed appointment, in a room away from interruptions and disturbances (as far as possible in a busy college) and recorded onto cassette tape. In addition the style of the conversation has been didactic, and unlike ones that subjects are familiar with in the teaching situation in that

(i) extended series of questions are asked of the same student (compared with the sharing round of questions in a class that often allows a shrug of the shoulders, or vague comment, to deflect a question onto another student);

(ii) the balance of talk has been much more evenly shared between the two participants (whereas in classrooms most of the talking is usually undertaken by the teacher, Sutton, 1974, p.42; White, 1988, pp.113-114); and

(iii) much time is spent exploring the subjects' ideas, and little (if any - see below, §4.10.3) time is spent transmitting the teacher's (i.e. researcher's) views.

§4.7: Kelly's construct repertory test.

§4.7.1: A brief overview of Kelly's methodology.

George Kelly has been considered by those concerned with constructivist approaches to science education to be one of the key antecedent thinkers. His theory of personal constructs (P.C.T.) was outlined in chapter 2 (§2.2.4).

Although Kelly's ideas have been used as a foundation for the constructivist position, most research into student understanding of science has ignored his *methodology*: the techniques of triads and the repertory grid. In the present study Kelly's method of the construct repertory test was used as a data collection technique to inform and supplement interviews.

Kelly's *construct repertory test* and *repertory grid technique* were designed for use in psychotherapy, and were used to find out how the client viewed aspects of his world. Often the components of the client's world used as foci were other people. The names (or roles) of significant people in the client's life would be written on pieces of card. These were referred to as 'elements'.

In the *construct repertory test* triads of elements would be presented to the client who had to divide them into a pair of elements that were construed to be in some way similar, and the one that was different (Bannister and Fransella, 1986, p.49). The discrimination was considered to be on the basis of the elements being nearer different poles of a (bipolar) construct used by the client to structure his or her world. By working though all the client's ways of discriminating in a series of triads, his or her significant constructs should be revealed. The *repertory grid* took this approach one step further: the client was asked to decide where each element should be placed on *each* of the bipolar constructs elicited. This gave a grid with columns (elements, categorised in terms of the constructs) and rows (constructs, used to discriminate between the elements). It was then possible to compare similarities between rows, and find a hierarchy in terms of the similarity in the way the client used his or her various constructs and thus reveal how constructs were related (Bannister and Fransella, 1986, pp.51). Grids allow statistical analysis, but the construct repertory test is considered to be sufficient where such analysis is not required (p.52).

In the present study this method of triads was used to elicit the constructs that student colearners use to discriminate between examples of representations of the microscopic structures discussed in chemistry (atoms, ions, molecules etc., see §5.1.4) Data was tabulated, and in some sessions colearners were then asked to decide whether other elements were construed at the disclosed pole of the elicited constructs (i.e. the 'emergent pole').

§4.7.2: Appropriateness of Kelly's methodology to the present study.

Kelly applied Personal Construct Theory as a therapist: i.e. largely in terms of how people construed their *social* environment, rather than the *physical* world. P.C.T. was devised in the context of therapy, not education (Solomon, 1994, p.7). Kelly and his advocates would agree that his theory and methods arose from that particular context, but not that they were limited by it. Kelly believed that systems have *foci of convenience* where they tend to be *most* effective, and for P.C.T. Kelly believed this was "in the area of human readjustment to stress" (Kelly, 1963 {1955}, p.12). But Kelly devised his psychology to apply to all situations where people construe meaning (Bannister and Fransella, 1986, p.4, p.21, p.44; Kelly, 1963 {1955}, p.130).

Kelly's theory concerned personal *constructs*, where the present study is concerned with *concept*ual development. It is therefore appropriate to ask whether constructs and concepts are the same thing, and if not, how they are related. The *Oxford Companion to the Mind* defines *concept* as "an abstraction or general notion that may serve as a unit (or an 'atom') of a theory" (Gregory, 1987). A dictionary of psychology suggests that a *concept* or *conception* is "that type or level of cognitive process which is characterised by the thinking of qualities, aspects, and relations of objects, at which therefore comparison, generalisation, abstraction, and reasoning become possible, of which *language* is the great instrument, and the product of the concept - normally represented by a word" (Drever, 1964). That same dictionary describes 'construct' as just "a term which some writers ... have suggested as a substitute for *concept*" (Penguin Dictionary of Psychology).

Kelly himself, although preferring to use the term *construct*, suggested he did not mean something very different to *concept* (Kelly, 1963 {1955}, pp.69-70, see also Watts and Pope, 1985, p.9). If we accept that knowledge is personally constructed by individuals, rather than transmitted to them, then it is unlikely that any two students, or any two examiners - let alone a student and an examiner - will have exactly the same set of meanings for say 'covalent bond': with an exact agreement on examples and non-examples, and associations with other concepts. However, Kuhn has pointed out that science is not learnt in terms of agreed definitions (1977, pp.xviii - xix), and as has been pointed out earlier, total agreement is not necessary for science to proceed, as long as meanings are similar enough for effective communication most of the time (c.f. §2.2.3).

Lemke has studied classroom discourse in science lessons and concluded that *in practice* concepts may be considered "just bits of thematic patterns" as they are never used in isolation, and their utility derives from their interrelations (c.f. Vygotsky, 1986 {1934}, p.245, §2.2.2). He concludes that 'purely mental notions' of what a concept actually is tend to ignore the central role of language in learning (1990, p.91).

So although terms such as 'covalent bond' may be defined in text books and scientific dictionaries, students and practising scientists have their own personal meanings for the term. Fransella and Bannister conclude accordingly that studies of individuals' meanings for scientific concepts fall within the scope of Kelly's methods,

> "In theoretical terms *all* constructs are personal. Even constructs drawn from say science or technology which have highly publicly specified relationships and implications and which have had their predictive validity tested and retested are still personal. They are personal in the sense that each person has to acquire them and integrate them into his total system. ... there might be much of interest to be investigated using grids where the elements and constructs are drawn from areas of high public agreement."
> (Fransella and Bannister, 1977, p.117.)

There seems then to be justification in the literature for proposing that we may consider the versions of 'concepts' in students' minds as 'constructs' without doing violence to Kelly's original theory.

The core of Kelly's theory then was that people impose structure and meaning on their worlds, by making discriminations on the basis of a system of personal constructs. To elicit the constructs the therapist - or researcher - needs to present the client - or student colearner - with some foci with which to make a discrimination. It might be suggested that presenting two elements, and asking for ways in which they were similar and different, would suffice. However Kelly pioneered the use of *triads* of elements (1963 {1955}, p.112), which has an advantage that it allows discriminations to be made on the basis of tacit criteria, that may only be brought into conscious awareness in the act of making the discrimination or trying to verbalise the basis for the distinction.

Fransella and Bannister recognised the potential of the triad method to studies in learning science (1977, p.117). Whitelock (1988) has reported using the repertory grid technique as part of a study into 11 and 17 year-olds ideas about motion, and a recent paper by Fetherston (1997) has proposed a learning approach derived from P.C.T.

However those working in science education have generally preferred other techniques such as concept mapping (see §4.9.1), word association and - especially - interviewing (see for example, White and Gunstone, 1992, which might be seen as a manual of methods used in the field). One possible reason is touched upon by Osborne and Wittrock who suggest that many science teachers do not fully trust complex statistical methods (1985, p.63). So science education research within the constructivist tradition has sought to use Kelly's theoretical base to ***underpin*** other methods (e.g. see Swift, Watts and Pope, 1983, abstract). The main method employed has been interviews (e.g. Osborne and Wittrock, 1985, p.80).

To summarise my main points

- Kelly's methodology for applying his Personal Construct Theory, involved the presentation of triads of elements, and asking the client to make discriminations.
- This technique was sufficient to elicit a repertory of constructs used by the client in construing his or her world.
- Further analysis could be undertaken by recording the repertory of constructs on a grid, which was suitable for undertaking statistical tests.
- Although Kelly refers to ***constructs*** rather than ***concepts***, the distinction is not problematic as Kelly's theory encompasses scientific concepts, as well as distinctions made on affective grounds.
- Although researchers in science education tend to have avoided Kelly's methods when exploring conceptual development, the objections raised concern the analysis of grids, not the Construct Repertory Test (the method of triads) itself.

Kelly's method of triads is then a technique which is appropriate, in a research project which is ground in personal constructivism, for exploring aspects of students' meanings in science - although the literature suggests it has not been widely used for this purpose.

§4.8: Colearner dialogues.

§4.8.1: Researcher cuing: a potential difficulty for interviews.

The clinical nature of the conversations that take place in interview situations makes them somewhat removed from the normal discourse about science that occurs between students. In particular, the inquisitorial nature of the interviewer's role, imposes a very different social context than when students are working together in a classroom situation.

Solomon has suggested that the construction of knowledge in science classes is very much a social act (see chapter 2, §2.7). Edwards and Mercer have discussed the unwritten rules of classroom discourse, where the aim is often for the students to work out *what the teacher thinks* the answer to the teacher's question is, to give an appearance of coming to common knowledge through consensus - rather than the teacher just reporting the conclusions to be learnt. Edwards and Mercer's work - based on research in primary, middle and comprehensive schools (Maybin, 1987, p.171) - show that often teachers' questions are framed and cued in such ways that their purpose is less to test understanding, than to give an impression that the accepted knowledge has been reached through a process of dialogue (see chapter 2, §2.8.2).

In a research interview the researcher aims to take a very different role from the teacher: and rather than lead the respondent to the interviewer's understanding, he or she attempts to find out what the respondent *really* thinks and understands.

Edwards and Mercer point out that many questions asked by teachers defy the normal social conventions in that the inquirer already knows what the answer is: so when a classroom teacher asks "what is a covalent bond?", the purpose of the question is not to find out what a covalent bond is, but to see if the class can offer an appropriate response. Such questions are often asked at a point in proceedings when the teacher believes the students should be able to answer in an accepted fashion: indeed often when the proceeding teacher talk or question sequence has clearly 'telegraphed' the required answer. As Solomon point out, "teachers' questions are designed to elicit the right answer, if at all possible, because they teach as well as inquire" (Solomon, 1992, p.132).

However, in a research interview, 'the right answer' should be the one which clearly reflects the respondent's own thinking. In an interview situation the researcher may phrase the question in a more honest way (e.g., "so what do you understand by the term *a covalent bond*?"), and even if not (e.g., "so what *is* a covalent bond then?") the earlier context of the interview has made it clear the issue is not *what is meant by a covalent bond* in abstract, but what the particular student understands. Nevertheless, the social context of the interview, may mean that the student is concerned to please by producing the 'right' answer, and may pick-up unintentional cues provided by the interviewer's wording of questions, tone of voice, reaction to the responses etc. Indeed if the interviewer misjudges the knowledge available to the respondent, then the very questions asked could provide information that the student did not previously have available.

Unintentional interviewer cuing may be kept to a minimum by experience of interviewing, knowledge of the respondents, and prior awareness of the likely limits to student knowledge. In the present study:

- I had some previous experience of interviewing (in research for my Master's degree), although this was concerned with finding out about attitudes rather than conceptual understanding;
- before commencing the field work I had undertaken reading of the literature to find out about the range of reported misconceptions and difficulties students could have in the topic of chemical bonding, and in those aspects of school science considered prerequisite;
- I had several years experience of teaching the topic of chemical bonding to A level chemistry classes;
- the respondents were my student-colearners, so that I had my teacher's knowledge of their general performance in chemistry, and their understanding in the subject.

The question of cuing is complicated by the in-depth interview approach used: where the student-colearners were working in their zones of proximal development (§2.2.2) it is necessary to judge where the researcher-colearner provides *scaffolding* to find out what the student really understands, and where the researcher effectively *provides* an answer (see §4.10.4 below). Analysis of the interviews suggests that generally the answers given by respondents were not due to unintentional cuing. (In places where it appears I made misjudgments it was possible to ignore the responses during analysis.)

Nevertheless, I decided that it was appropriate to set up situations where some of the colearners would discuss the topic (of chemical bonding) without the opportunity for my cuing their responses. In this way it would be possible to see if the level of knowledge and range of ideas elicited was compatible with that found in the interview situation.

§4.8.2: Group discussions.

Gilbert and Pope report an approach to studying learners' ideas in science which involves setting up group discussions. Their aim was to provide a context where learners would develop their thinking about scientific topics (1986a, p.62). Their suggested solution was described as "peer-group discussions, built around a suitable stimulus situation, and organised in such a way as to promote challenges to conceptions" (p.62). They used this approach with middle school pupils in Germany, using groups of 2-3 learners, using a deck of cards designed for the 'interview about instances' technique (§4.6.2) focussing on the concept of energy. They found that the groups would carry out the task, although the quality of discussion depended on group composition (p.75).

They also found that the presence of a researcher in the group has a disproportionate impact, and changed the nature of the discussion to be more like a teaching context (p.74), whereas when the children were left alone the process would elicit a discussion rich in the their own ideas (Pope and Denicolo, 1986, p.159). Solomon (§2.7) has also collected and discussed samples of data from groups talking about energy-related topics (1992, pp.65, and pp.157).

§4.9: Supplementary material used to support the case studies.

My dual teacher-researcher rôle meant that I was working with the student-colearners in a classroom situation. This gave me the opportunity to see work they produced as part of their course. Some of this work was relevant to the topic of chemical bonding, and photocopies were made in these cases.

This material was used to authenticate the interview data. Some points arising from course-work were introduced as talking points in interviews - in such a case the focus of discussion had arisen from a suggestion of some alternative conception or confusion in the student's work, and if such a conception was then reiterated in the interview, it was not just an artifact of the clinical context. Even when the material was not used as a *starting point* for interview discussions it was kept on file so that a comparison could be made, allowing the opportunity to support or challenge interpretations of interview data. The type of material collected included copies of test scripts, as well as other set tasks, including concept maps (see below, §4.9.1). The validity of using data collected in such an opportunistic manner is considered below (§4.10.7).

In addition, 'incidental' data was collected from *other* learners, and this included responses to questions set as induction exercises at the start of the course, and to past examination questions used as tests, and student concept maps.

§4.9.1: Concept maps.

> "A concept map aims to show how someone sees the relations between things, ideas or people."
> (White and Gunstone, 1992, p.15.)

The concept map is a way of representing knowledge. In a concept map material is organised so that the key words, representing the concepts of the topic, appear highlighted in boxes at the nodes of the map. The relationships between the concepts are represented by connecting lines. Each line stands for a proposition relating two concepts. Unlike a linear text there is no single intended order for 'reading' the map: it is a network of ideas that may be sequenced in many permutations. The figure below is an example of a concept map for the concept of '*concept map*'.

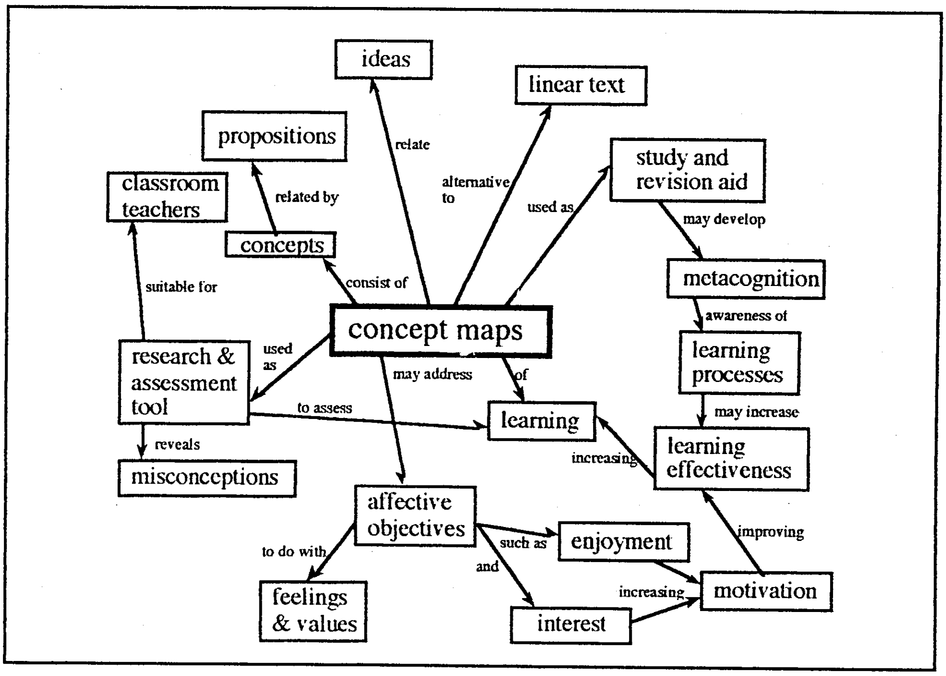


Figure 4.2: A concept map for *concept map*.
(Taken from Taber, 1994.)

The technique of concept mapping has been much discussed in the literature, as a learning tool and an assessment technique, and also as a classroom based means of diagnosing aspects of a learner's cognitive structure (Al-Kunifed and Wandersee, 1990; Edwards and Fraser, 1983; Watts, 1988).

Gilbert and Watts have suggested that research to explore learners' ideas should involve "*mapping the 'topography'* of local domains of understanding" (1983, p.66, my emphasis) and "*charting* changes in frames of reference so that the durability, stability, coherence and consistency of conceptual constructions become the point of departure" (p.67, my emphasis), and concept *mapping* would seem an idea approach.

I have used concept maps as a learning technique for some years, and so asking students in my chemistry classes to produce a concept map to summarise a topic area was a normal part of my teaching repertoire. Indeed, the figure above is taken from an article about concept mapping where I demonstrated that concept mapping could simultaneously lead to diagnosis of student 'misconceptions', be an activity that students enjoy, and could encourage metacognition (Taber 1994).

The article described how a group of A level physics revision students were asked to produce a concept map for the topic of energy. A number of 'misconceptions' were elicited, including a suggestion that "some chemicals when combusted give out energy in the form of heat due to the breaking of bonds". On this occasion the students were asked to jot down their feelings about the exercise and their comments were generally positive. The students recognised how the activity tested their knowledge ("I think this exercise was useful as it let me know exactly how much I know about energy, which I can now see is not enough"), and provided them insights about their current understanding ("my knowledge of physics is very un-organised at present"). The open ended nature of the activity encouraged students to explore their thinking of the topic ("at first I did not know where to start but as I began putting ideas down, it reminded me of other points"; "[I] did not think I would have been able to think of enough things after 3 months but found things start to come back once I started writing"), and the act of organising their knowledge into a map seemed to provide a learning experience ("I didn't realise how much the different areas interlinked"; "quite useful, brings back memories; good to see how well topics relate or how well you can interrelate them"). Indeed as one student explained,

> "I found I was digging around, trying to put fragments of things I could remember together. I found I could remember only scraps of information, but when doing the drawing [sic], saw how things pieced together, and linked with other things"

Therefore, in my own experience, concept mapping is a technique which can be used to survey a group's initial ideas about a topic, or to evaluate aspects of their learning; but it is also a technique which is useful for students as it enables them to make explicit connections ("I saw how things pieced together, and linked with other things"), and to evaluate their own progress ("it let me know exactly how much I know"). As opposed to a test where the format encourages elicitation of information in a specific order, the concept map allows the student to access ideas in a much more flexible way.

In the present research therefore, I was able to ask students to produce concept maps of topics at various stages in their course, using the information for my research, without compromising my 'teacher' role, and the students' right to expect me to set work for pedagogic purposes.

§4.10: Issues of authenticity, and generalisability.

In a sense, this entire chapter is largely concerned with issues of the authenticity and generalisability of the research reported in this thesis. In this final section of the chapter some specific concerns will be discussed.

§4.10.1: Notions of reliability, validity and authenticity.

Any researcher presenting results to the public domain has to be prepared to defend the integrity of the methods of data collection and analysis used in that research. Traditionally the notions of *validity* and *reliability* are considered to be of great importance. Essentially a research instrument is reliable if it provides reproducible results, and is valid if it measures what it claims to measure. For example in the present study, if one of the foci diagrams used to elicit learners' ideas about bonding was intended to represent a certain type of bond, but was not recognised as such by learners who *would* recognise other (e.g. text book) representations, then this would not be a valid probe.

Reliability is a more problematic criterion in the context of the present research. With some quantitative instruments reliability may be gauged by finding the test-retest coefficient - but this is obviously not appropriate in the present research, if only because student answers are expected to change over time: that is part of what is being studied. It is also inappropriate because question phrasing and ordering are flexible, and the sample size would be too small.

Within an interview the reliability of the researcher's interpretation of a colearner's comment may be checked (see appendix 11 for examples from the case of Annie) in a number of ways, including:

1) confirming responses by repeating or rephrasing questions (see appendix 11, §A11.1);
2) clarifying ideas by asking follow-up questions (§A11.2);
3) paraphrasing what one believes to be the colearner's argument, and

seeking confirmation (§A11.3);

4) returning to the same point in the same context later in the interview, to see if a consistent response is given by the colearner (§A11.4);
5) approaching the same point through a different context later in the interview, to see if the colearner gives a consistent response in the different contexts (§A11.4).

However this does not mean that obtaining an apparently contrary response *necessarily* invalidates the data, and it should therefore be automatically discounted. Part of what is being investigated is the stability and lability of a student's ideas (e.g. see chapter 7). If a colearner's thinking is very labile, then this is an important feature which should be recorded in the results. If the colearner is operating with multiple alternative frameworks (see chapter 2, §2.5.2 and §2.9) then essentially the same question, but phrased slightly differently - or just cued differently by the particular examples and ideas discussed immediately prior to the question - may well lead to inconsistent responses *without* suggesting that the technique and data are unreliable. Indeed when an apparently inconsistent response is obtained it is possible to then ask about the earlier comment, and often this is most revealing. In the type of approach to data collection and analysis taken here, the negative case may be used to explore and test the range of application of ideas (Walker, 1993, p.177, and see §4.6.1) and thus to refine categories and concepts.

The difficulty of applying the criterion of reliability to interpretative research, undertaken using qualitative methods, has led to the suggestion that it is more appropriate to judge such enquiry by notions of *authenticity*. The researcher's presented results (i.e. interpretations) should be true to the data (Pope and Denicolo, 1986, p.156, see also §2.4.2, §4.2.5, §4.4.5 and §4.10.6 regarding the danger of 'framework spotting'). Appendices 26 and 27 provide an insight into the analytical decisions made in the present research. Appendix 26 gives an example of how transcripts from interviews with colearner Annie were edited in preparing a study of her case (outlined in chapter 7). Appendix 27 shows how preparing Tajinder's case study (summarised in chapter 8) involved a number of stages of analysis (§A27.0), integrating data from interviews and other sources. This appendix shows how the information in an extract from one interview transcript (§A27.1), is used in preparing a narrative summary of that interview (§A27.2), and then a thematic summary reorganising the material according to the topic (§A27.3), which was then used to prepare the case study document itself.

The need to produce authentic accounts from the data collected has resulted in the decision to concentrate on two colearners when presenting results: one from the first cohort of colearners (see chapter 7), and one from the main cohort (see chapter 8). The limitations of "time and concentration from interested readers and space" (Pope and Denicolo, 1986, p.156) meant that in-depth case studies of all the colearners for whom sufficient data was available would have led to a tome of unacceptable size. The material from the other colearners is treated in less depth in this thesis. However, as explained above, this is appropriate in grounded theory. The case studies stand in their own right as part of an idiographic tradition of research into individual learners, but they also form the early stages of the analysis which led to a model (of A level students developing thinking about chemical bonding, see chapter 6) which is grounded in the wider database.

§4.10.2: Information flow in the interviews.

The purpose of the interview is for the researcher to find out about the ideas of the colearner, rather than to impart information to him or her. It would be possible to consider a *model* for interviewing where the researcher collects data from a student, without releasing any substantive information. (This does not mean such an approach would be possible in practice, as any question is 'loaded' with assumptions.) In the present study such a model was not followed: information was sometimes deliberately given to the colearners. This intention was related to both ethical and methodological implications.

For ethical reasons (§10.4.3), it was sometimes appropriate to provide feedback at the *end* of a research session, to highlight errors or limitations in the colearner's thinking. If the feedback was effective, then subsequent interviews would demonstrate a different level of understanding than would have been present without such intervention. This means that the development of understanding of chemical bonding amongst the colearners might be 'accelerated' compared to 'typical' students. However, as the study was not intended to survey a representative sample of A level chemistry learners, this was considered quite acceptable.

In methodological terms (§10.4.4), I was aware that my foci diagrams, the thrust and wording of my questions, my reactions to student responses (including the decision how to follow-up responses with further questions) all provided cues that moved my clinical interviews away from a purely naturalistic study of student thinking. Given that my research techniques were interventions, I had to use my judgment to decide how much information to give, to best probe a colearner's thinking, so that my data reflected the student-colearner's ideas rather than my own. When analysing interview data the cues provided to colearners were taken into account when drawing inferences from their comments.

§4.10.3: The ethical perspective: the researcher's duty to inform colearners.

It was explained above that it was felt important that the research interview sessions were of value to the colearners, and were perceived to be of value by them (§4.3.2). Colearners were volunteers, and could only be expected to volunteer again on a subsequent occasion if they found the experience rewarding. (Indeed, even if a colearner appreciated the value of the session, they might not want to repeat it, if they found it particularly stressful.) My own role for these young people was primarily as one of their lecturers, and they rightfully had expectations of me in that role.

During the early phase of the project I attempted to conceptualise my teacher and researcher roles as largely separate: I would teach the students in class, but enquire into their understanding during research interviews. I hoped that the colearners would benefit from the conversations, and would become aware of their own areas of difficulty. As I was interested in observing the development of student understanding, I had reservations about actively 'teaching' colearners through my research. However, the use of clinical interviews was already a form of 'intervention' (so that an anthropological model of the research was already inappropriate), and the insights that might be gained from research interviews would be likely to influence my behaviour as a teacher (which, after all, is the purpose of undertaking educational research, see §4.1.2). In a sense, my decision to take on the dual teacher-researcher role, and research *my own learners* had placed my study within an action research frame. The duty I owed my colearners, as part of the implicit contract for taking part in the study, demanded that they should be informed about their 'performance' in interview (§4.3.2).

The colearners were understandably concerned to know 'how well they did' and 'what they got wrong' during an interview. This second question was not so easy to answer, and I explained that it was often not so much 'getting things wrong', as a question of ideas becoming more sophisticated over time. Whilst this was true, it was clear the colearners felt they needed more specific feedback, and they were able to ask me for this as I was their teacher. Sometimes the interviews acted as a learning experience for the colearner, because by being led through the consequences of an idea he or she comes to find that it is wrong, and moreover to see for herself *why* it is wrong. In these cases the 'lesson' may be well learnt. On other occasions the interviewer's questions may *not* lead to the colearner contradicting his or her own knowledge, or producing an argument that he or she *considers* inconsistent or circular or teleological or ridiculous. (The student-colearner, of course, may not posses the same criteria for a good explanation as the researcher-colearner.) It is on these occasions that feedback is required at the end of the interview.

Annie's interviews revealed she had an alternative conception of the meaning of electrostatic charge symbols (see chapter 7, especially §7.2.2). Whilst the full extent of the implications of her alternative notion only came clear on detailed analysis of the transcripts *after* she had finished her course, it was apparent at the time of the early interviews that Annie had some problem understanding this aspect of CURRICULAR SCIENCE During this phase of the project a sequence of three interviews was planned for each colearner, and during the final interviews I was aware of the provisional analysis from the previous two sessions. During Annie's third interview - shortly before her final examination - it became clear that she still held the 'incorrect' notions I had identified after her second interview. At this point, it seemed appropriate that - as her teacher - I should provide a detailed debriefing after the interview on this aspect of her ideas. We also agreed to an additional fourth session soon afterwards to see if Annie had been able to adjust her thinking.

In retrospect it became clear that such a debriefing should be provided for all colearners immediately after an interview, and this was included in the second phase of the research (interviews with Edward, and the second main cohort, i.e. Jagdish onwards). Although I was tape-recording the interviews for later analysis, I decided I needed to respond to the request for specific feedback, and changed my procedures for the main study, to include brief contemporaneous notes of points that should be fed back at the end of the interview. In this way the actual research design was changed in response to the colearner's needs - and what they were entitled to expect.

§4.10.4: The methodological perspective: working in the zone of proximal development.

During the first stage of the study (January 1991 - May 1992) it became clear that the research interview could be a learning experience for the student-colearner in terms of giving the students the opportunity to learn through the process of talking through their ideas. This observation is consistent with the literature reviewed in chapter 2, where Vygotsky's ideas of words-as-tools, and the Z.P.D. (§2.2.2), and Edwards and Mercer's studies of classroom discourse (§2.8.2) were discussed. Bruner and Haste discuss how one function of discourse may be as scaffolding (1987, p.21), and in a similar vein Gallimore and Tharp (1990, p.181) explain how questioning may *assist performance*. Bruner (§2.2.3) has described how language acts as a *cognitive instrument* for representing and *transforming* experience (1977, p.210).

Perhaps the most dramatic example of this was one of the colearners in the main cohort, who was able to explain the nature of van der Waals' forces (although she did not have a name for them) - even though this was not a topic that had been studied in class. After working through her argument the colearner's own reaction was surprise - this was something she had not 'known' until that point, and she apparently constructed this knowledge from what she did know *in situ* in front of researcher and tape-recorder (see appendix 8). The in-depth nature of the interviews is similar in form to the Socratic/Platonic method of dialectic, where, "one pursues a topic with inexorable patience, by questioning and answering, and one shakes it and pulls it this way and that..." (Egan, 1983, p.32).

To my own mind the interviews gave an opportunity for colearners to explore and 'play with' scientific ideas in a way that I thought it was unlikely to occur otherwise: the method was 'invasive' and therefore the research act itself formed an important part of the context of the conceptual development being explored (e.g. Pope and Denicolo, 1986, pp.154-155).

Vygotsky's idea of the Z.P.D. (zone of proximal development, see chapter 2, §2.2.2) is very relevant to what actually occurs during interviews: the conditions in the interview seems to be just those where Vygotsky would expect learning to take place - what Kozulin has described as "the place at which a [learner]'s empirically rich but disorganised spontaneous concepts 'meet' the systematicity and logic of adult reasoning" (1986, p.xxxv).

Driver and her coworkers have actually suggested that intervention *should* be a deliberate part of any study looking at how ideas change,

> "Longitudinal studies, which track the the evolving conceptions of individual students over extended periods of time, can provide detailed information about learning routes and enable features of students' developing knowledge to be characterised, but do not necessarily provide information about what prompts change and how it occurs. In order to obtain information of this kind, it is necessary to study students' learning in science as a consequence of specific interventions." (Driver et al., 1994b, p.85.)

Undertaking research interviews is a skilled process: in order to be able to claim that a respondent's utterance gives evidence for the presence of a successful understanding or the use of an alternative framework the interviewer has to be aware of the whole context of the utterance within the interview. An earlier comment by the interviewer, or a leading question, may undermine (or alternatively illuminate) the evidence. The interviewer should not 'correct' or offer evaluation of the respondent's comments *while* trying to explore her or his thinking. Indeed the order of questions and the use of particular words that may cue or trigger a response needs to be carefully thought through. For example Tomlinson (1989) has discussed how the the interviewer can use 'hierarchical focussing' to maximise the amount the respondent spontaneously introduces, whilst ensuring that the interviewer's full agenda is covered. In the present study the use of a sequence of prepared focal diagrams (with the possibility of changing the sequence as required) was used to address the research agenda. As interviewer, I had to decide at all times how much cuing to provide through the questions asked. These decisions were made in response to the colearner's comments and behaviour in the interview, as well as my knowledge of earlier interviews with the same and other colearners.

Although the main data collection technique used in this study has been the interview, the authenticity of the results has been enhanced by ***methodological triangulation*** - using the construct repertory test as an alternative approach to elicitation, and with alternative foci; collecting samples of the student-colearners' talk in peer discussions; and collecting course-work such as concept maps (§4.5). Data has also been collected from learners other than the colearners who undertook the interviews that form the principle data source. The importance of this form of triangulation to interpretive inquiry has been emphasised by Guba,

> "The naturalistic investigator is concerned with description and understanding; thus, he begins as an anthropologist might begin learning about a strange culture, by immersing himself in the investigation with as open a mind as possible, and permitting impressions to emerge. As impressions are formed, he checks them out by various means, e.g. 'triangulation', testing one source against another until he is satisfied that his interpretation is valid."
> (Guba, 1978, quoted in Gilbert and Pope, 1986b, pp.41-42.)

§4.10.5: Case studies and generalisability.

> "Any theories which are developed must be grounded in the actual data the researcher has. This results in interpretative researchers only moving from discussion of individual cases to wider, general situations when they have achieved a close, detailed description and explanation of those individual cases."
> (Hitchcock and Hughes, 1989, p.29.)

One criticism that has been made of case studies is their "limited reliability and validity" as representative of a wider class of cases, that is what has been labelled *the generalisation problem* (Walker, 1993, p.166).

However, a case study is by definition not *intended* to produce findings to be generalised: the whole purpose of carrying out case studies is to allow the in-depth study of the *particulars* of an individual case (Hitchcock and Hughes, 1989, p.32). That is not to say that a case study can not illuminate other cases: it provides insights which allow other cases to be approached in a more informed way - both in terms of data collection and analytical approaches, and in terms of hypotheses against which the researcher may test the data. The case study of Annie presented in this thesis is about the individual (labelled) Annie, rather than some general notion of 'the A level chemistry student'. Tajinder is another individual, and his case study attempts to describe his progress in understanding chemical bonding, rather than Annie's, or 'the A level chemistry student' in general.

Although such case studies are fascinating, and - because of their longitudinal and in-depth nature - are illuminating to others looking at conceptual development, they do not allow general conclusions to be drawn about difficulties in learning chemistry; general conclusions that could form the basis of useful pedagogic advice to science teachers. This would require an analysis of data from a larger sample of learners. This is why, in the present study, case studies have been used as part of a strategy of analysis to produce grounded theory, rather than simply as an end in themselves. Hitchcock and Hughes warn that before case studies can be used as the basis for developing a wider view the researcher needs to have an in-depth understanding of those cases (motto above): by presenting summaries of the individual cases of Annie (chapter 7) and Tajinder (chapter 8) I am demonstrating that I "have achieved a close, detailed description and explanation of those individual cases".

§4.10.6: Framework spotting.

An individual learner has a *unique* cognitive structure (§1.4), and in idiographic research (§4.1) it is possible to produce descriptions of (the researcher's models) of aspects of an individual's ideas: in the present thesis chapters 7 and 8 do just this. However, it is also possible to produce models which act as descriptions of *common patterns* in learners' ideas (see chapters 6 and 9 to 11). In chapter 2 (§2.4.2) this distinction was described in terms of ALTERNATIVE FRAMEWORKS$_1$ and ALTERNATIVE FRAMEWORKS$_2$. Kuiper was criticised for ignoring this distinction, and consequently undertaking what Pope and Denicolo have described as "a 'framework spotting' exercise" (1986, p.157).

However, providing that the status and derivation of proposed *models of common aspects of learners' thinking* are understood, such 'products' can be of value to teachers. Awareness of the range of likely alternative conceptions members of a class may hold is useful before setting out to teach a topic (for example to overcome potential SUBSTANTIVE LEARNING IMPEDIMENTS, §1.5.3). Understanding of any common features to students' alternative frameworks for a concept area, can allow to the teacher to be sensitive to the possible meanings that students may have for the words they use, and allow the teacher to make sense of otherwise unclear student statements and questions. The teacher who wishes to build a common understanding with a class will need to learn the students' 'language' for the topic: and research results may act as a useful starting point. For a teacher committed to a constructivist perspective, it is essential to know what foundations are available for building new knowledge (c.f. §2.3.9 and §.2.3.10).

In the present research then I considered it important to draw out from the data features that may be significant for teachers approaching the topic of chemical bonding (see chapter 12, §12.5).

§4.10.7: The validity of opportunistic data collection: anecdotal evidence?

Research data is normally collected in a systematic way: it is expected that an enquiry will be to a purpose, and will be planned accordingly. However, in the present study it could be claimed that some of the supplementary data was collected 'opportunistically' (c.f. 'accidental sampling', Cohen and Manion, 1989, p.103).

By 'opportunistic' data collection, I am referring to taking the opportunity to collect data that might be relevant to a study, as one 'stumbles across it'. This process is not planned, is not systematic, does not provide any control over 'variables', and does not allow any gauge of the representative nature of the data collected. The term that might often be used is 'anecdotal evidence', and it may be suggested that such material has no role to play in research.

Here I will argue that the distinction between data collected systematically and opportunistically is not a dichotomy, but rather there is a continuum that is related to the research paradigm in which the research is ground (§4.1). From within the experimental research tradition, data would be collected in a preplanned and predetermined manner: the number of data, as well as the nature of each datum are tightly regulated. Variables are controlled, data is often quantitative, and statistical analysis may well be appropriate.

The interpretative research tradition does not usually share these features. For example, in ethnographic research, the aim is for the researcher to immerse him or herself in the culture being researched, and to observe, and to attempt to understand the meaning that others give to their actions. The greater the preplanning of how and when data would be collected, and the nature of the data to be collected, the more assumptions are being made about the culture which is being explored. Yet the nature of such research actually requires the researcher to attempt to minimise preconceptions, and to limit his or her reliance on existing theoretical frameworks. It is accepted that in such research the categories by which data are recognised and analysed 'emerge' from the data (c.f. §4.4). The researcher role is to enter the correct context, and to be as open-minded about what is seen and heard as possible. To a lesser extent, the choice of semi-structured interview techniques, reflects an ethnographic approach (§4.1.1). Although the context is clinical, and prepared probes are used, the interviewer ***attempts*** to listen carefully without preconceptions to the informant, and to enter into his or her 'language community', and explore the topic from his or her world-view, rather than to simply judge her comments against the researcher's own constructs.

In this study I supplemented data from the clinical research, with 'incidental' data collection of samples of student course work. This could be described as 'opportunistic' data collection. However, it was data collected from a context - work done as part of an A level chemistry course - which was more directly relevant to the normal context of learning A level chemistry than my research interviews. It could be argued that this was the more authentic data. The data was collected in a less systematic way than the student utterances in interviews, or constructs elicited from triads. However, the data was not random: apart from the relevance of the context of the work (an A level chemistry course), I collected material that my own analysis of the topic area suggested would be of value to the study.

I kept notes of some student comments in tests, homework, etc., that were judged to inform my own understanding of the range of student ideas in certain topics (i.e. I have undertaken 'theoretical sampling', see above). This 'field data' supplemented the more systematically collected data, and was used to refine the categories which emerge from analysis of the interview data (c.f. §4.4.4). This ethnographic approach has been used effectively by Driver. In her seminal book, *The Pupil as Scientist?* (1983) she describes in the preface how "examples of pupils' dialogue and written work ... were collected while making a study over a 4-month period of a science class", and how "further examples", mostly from classes she had observed and taught, were also used.

In their discussion of grounded theory (§4.4) Glaser and Strauss explain how anecdotal data may be admitted when generating theory. For them the *anecdotal* *comparison* provides one *slice of data* (§4.4.2), which can be used as part of the process of triangulating between different data sources (1967, p.67).

§4.10.8: Diagnostic Instruments.

Whilst opportunistic data collection can provide a useful source of data from the 'normal' culture of science learning, against which to authenticate data collected from interventions, the only reliable way to gauge the *degree* to which specific student conceptions are widespread is to conduct a survey using a significant sample size.

The model developed in this thesis (presented in chapter 6, illustrated in chapter 7-11, and discussed in chapter 12), was grounded in data collected by research in the 'interpretative' tradition (§4.1). It is accepted that the results of such grounded theory "may later be verified through traditional logico-deductive methods" (Charmaz, 1995, p.48, §4.4). In the present study the thesis is largely concerned with *presenting*, and *providing evidence to support*, my model of A level student developing understanding of chemical bonding. The present study did not set out to provide a large, representative survey of chemistry learners.

However, some attempt was made to demonstrate how this might be done. Two 'diagnostic instruments' were prepared, piloted and then presented to a moderately large number of learners, based on aspects of the findings from the interview studies. These two instruments were:

- The TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT (see appendix 2);
- The TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT (see appendix 3).

These instruments demonstrate how aspects of the model developed in this thesis may be used to provide diagnostic tests for classroom use, and in doing so provide the potential for testing the model against a large sample of learners. The outcomes of this limited survey (described in the appendices) have been noted at the relevent points in chapters 10 and 11. In this feasability study these instruments were used with a sample of learners that was an order of magnitude larger than the number of colearners contributing to the research: *inprinciple* they could have been applied to a much larger sample size still.

Chapter 5.

Description of Methodology.

§5.0: The purpose and structure of the chapter.

In the previous chapter the research methodology applied to this study was outlined and justified. In the present chapter the techniques of data collection (§5.1) and analysis (§5.2) are described in more detail. The origin of the categories used to analyse the data will also be considered (§5.2.3 and §5.2.4). The mode of analysis of the interview and other data will be described: including the transcription procedure (§5.2.2), the manner in which transcripts were used to construct cases (§5.3), and the stages in which the model in chapter 6 was derived (§5.4).

§5.1: Details of data collection techniques.

§5.1.1: Interview procedure.

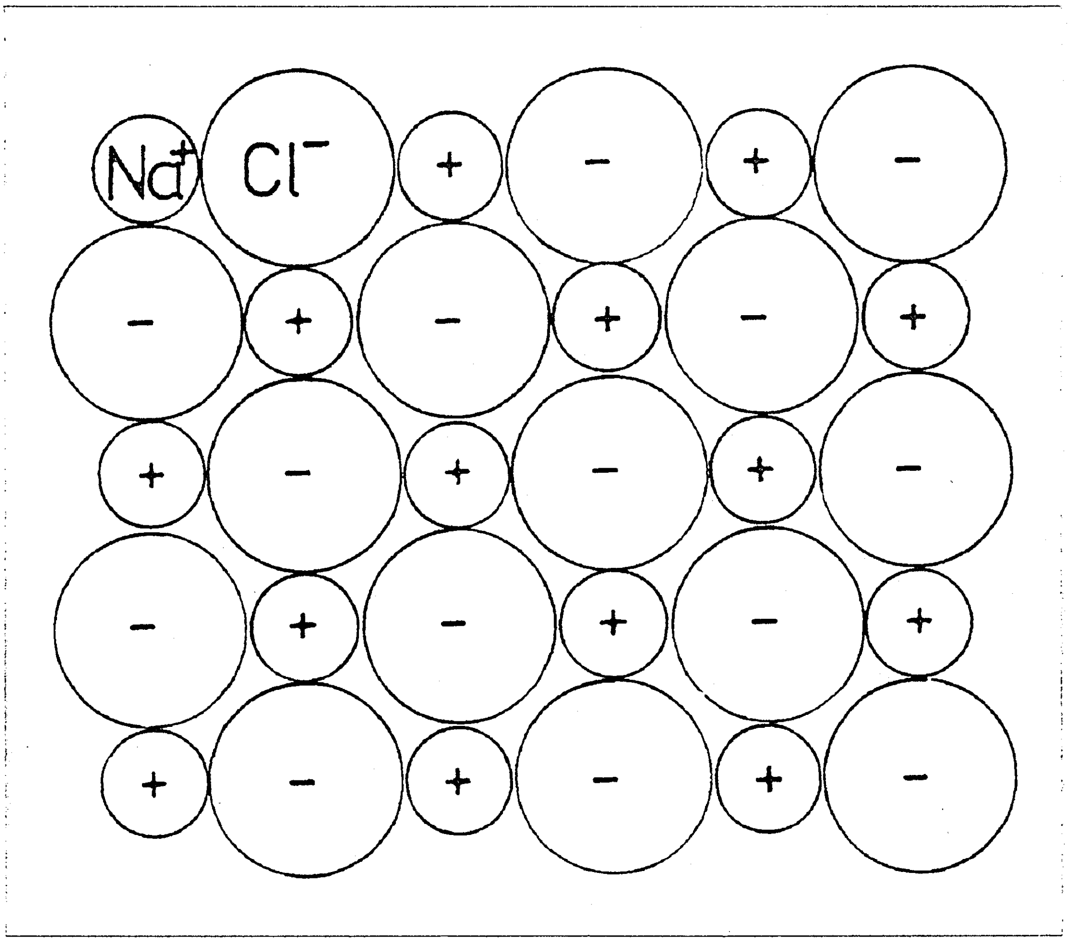
At the beginning of the first interview given by a colearner he or she would be told as part of the introductory comments,

> I am conducting some research into how students learn about chemistry during their A level course. I am going to show you some diagrams, and ask you some questions about them. I want to explore your ideas and your understanding so I will often follow up your answers with more questions, and I may challenge you to try and explain your ideas. In order to probe your ideas I will not be judging your answers as right or wrong but will try and explore what you really think. So I may seem to go along with answers that I don't think are quite correct, and I could seem to disagree with others, even if I really agree with what you have said.

As discussed in chapter 4, the interviews followed the 'interview-about-instances' approach (§4.6.2) "using a series of pictures as a focus" (Watts, Gilbert and Pope, 1982, p.11).

§5.1.2: The focal diagrams.

Focal diagrams for use in the interviews were drawn on A4 sheets. The diagrams were prepared manually, but as neatly as possible. For example, the image from focal figure 5 is reproduced below:



focal figure 5

Initially a deck of 17 diagrams was prepared, although this was considerably supplemented during the research in response to on-going reflection and analysis (c.f. §4.4.1).

The original deck of 17 diagrams is reproduced in appendix 12. The figures were intended to provide opportunities to talk about aspects of chemistry that had been identified as significant: atomic binding (focal figure 1), covalent bonding (2, 4, 7, 17), ionic bonding (5, 9), metallic bonding (5), polar bonding (3, 8, 10, 11, 14, 15, 16), multiple bonding (4, 12, 13), hydrogen bonding (11), dative bonding (15, 16), van der Waals' forces (17) and resonance (12, 13, 14).

As a result of reflecting on the data obtained during interviews, additional focal figures were added (i.e. there was *theoretical sampling*, §4.4.1). In order to elicit colearners' understanding of relevant notions regarding forces, a sequence of figures representing contexts for discussing forces was prepared. The early figures in this sequence were designed to have little obvious connection with chemistry (e.g., a falling apple), but later figures represented configurations of charged particles that could represent atoms or molecules (see appendix 13).

Additional focal figures were also produced to expand the original deck of diagrams of chemical species. A further 17 diagrams representing chemical species were prepared during the time the first cohort of colearners (Annie to Debra) were being interviewed. These are reproduced in appendix 14. As a result of reflecting on the data collected from this cohort, and from subsequent on-going data collection a further 15 figures were added to the deck during the time the interviews with the second cohort (Jagdish to Umar) were being undertaken. These are reproduced in appendix 15.

The additional diagrams of chemical structures were designed to complement the initial 17. They were produced for a range of reasons. For example, if I was unsure whether a colearner's comments were influenced by the type of representation used, perhaps channelling their thinking in a particular way, then an alternative representation might be construed differently. Some new figures were meant to represent bonding phenomena not covered in the original deck to provide additional contexts to discuss learners' ideas.

Some of the additional figures, such as focal figures 18 and 30, were meant to provide a more explicit context for discussing orbital ideas. Other figures were intended to focus student thinking on the electrostatic nature of interactions at the molecular level. As the significance of 'octet thinking' (see chapter 11) amongst colearners emerged during analysis, some diagrams were prepared to challenge this. Examples of the rationale for adding specific new figures to the deck are provided in appendix 16.

§5.1.3: Interview questions.

Part of the rationale for selecting interviewing as a technique is its inherent flexibility (§4.5). Therefore there was no detailed interview schedule prepared before the research commenced (§4.6.2).

It was intended to work through the deck of figures, and to *start* discussion about each by asking colearners three questions:

a) what was the figure meant to represent?
b) was there any bonding in the species/substance represented?, (and if so)
c) what type(s) of bonding?

Often - especially once the colearner became accustomed to the questions - the second and third questions were taken as implicit in the first. The interview style was informal, and a fixed form of precise wording was not thought to be appropriate. So, for instance, in the first interview undertaken the actual form of these question used included:

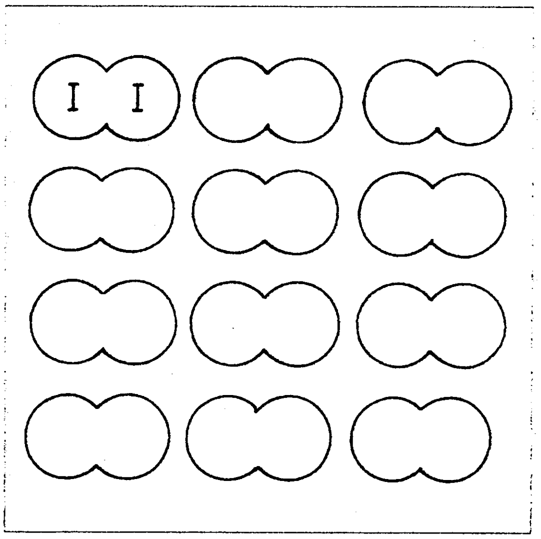
- "I wonder if you can tell me what you think it's meant to be?"
- "Any idea what that's meant to be?"
- "What do you think this is?"
- "What about this, any idea about this?"

- "So would you say there is a chemical bond there?"
- "Are there any bonds in that diagram, do you think?"
- "Is there any bonding in that molecule?"
- "Would you say that there was any kind of bonding there?"
- "Do you think there is any kind of bonds between the atoms?"
- "So in that diagram, have we got any kind of chemical bond?"
- "Can we see any bonds there?"
- "Are there any bonds, do you think, in that picture?"
- "Is there any chemical bonding there?"

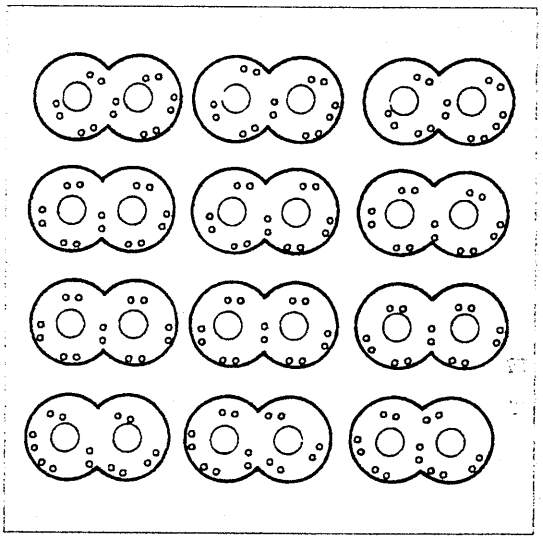
- "Any idea what kind of chemical bond that would be. Would you give it a name?"
- "What kinds of bonds are they?"
- "Right, what kinds of bonds have we got there do you think?
- "Do you know what kind of bonding that might be?"

One of the 'issues' that concerned me when I commenced the research was the distinction between the representation and that which is represented: and the extent to which aspects not made explicit in a diagram are understood by the learner to be implicit.

For example in focal figure 26 the arrangement of electrons is intended to imply synchronised (transient) dipoles to an observant interviewee. This is not shown in focal figure 17, *but* the van der Waals' interaction that *results* from the synchronisation of the dipoles could be seen to be *implied* by the representation of the molecules as occupying lattice positions as in a solid. Therefore for a colearner to explain why he or she thinks focal figure 17 shows van der Waals forces a substantial chain of inferences could be invoked. However, this does not necessarily mean that the colearner is consciously aware of this chain of logic in suggesting focal figure 17 represents a substance held together by van der Waals' forces.



focal figure 17



focal figure 26

In practice, the flexibility of the interview process - that enabled re-wording of questions, and paraphrasing of responses so they could be reflected back at colearners for confirmation or otherwise - enabled the figures to effectively provide foci to launch discussions about types of bonding in various materials, without the mode of representation being a major problem. That is, *generally* once a figure was perceived as representing a substance or class of substance, the colearner's background knowledge and understanding tended to be accessed regardless of specific aspects of the representation. There were some exceptions to this, so that there were occasions when Kabul would answer questions based on his reading of a figure, although he did not think his answers related to the *actual* structure of the substance represented (see appendix 36, §A36.1.12). Also, some aspects of some of the figures were challenged or queried (the representation of electrons in pairs in figures such as focal figure 21, and two of the electrons in focal figure 4 that were judged as 'not doing anything'!)

Where the mode of representation *did* seem to be a major constraint on responses this was often found to be a significant clue to student thinking. So for example focal figure 14 was sometimes taken to mean that boron trifluoride contains covalent ***and*** ionic bonds at the same time because the canonical forms were independently read as molecular structures. This often suggested an ignorance of resonance (§9.4.3), but also an acceptance of a dichotomous classification of bonds (§11.6). Similarly focal figure 15 was often interpreted as ionic (as a compound of a metal and non-metal, ignoring the mode of representation), or as covalent (due to the mode of representation, but ignoring the electronegativity difference). That these classifications continued when colearners had demonstrated that they had the concepts available to consider an intermediate option was found to be characteristic of a common way of thinking about chemical bonds (§11.6.2).

§5.1.4: The triad elements used in the present study.

In chapter 4 the rationale for using George Kelly's construct repertory test in this research was established (§4.7.2). In this study my main technique has been interviews, using foci diagrams I prepared especially for the research. With the method of triads, as well as the mode of elicitation being different, I decided it was appropriate to use different foci diagrams from those used in the interviews. For the triads I have built decks of cards by photocopying diagrams from text books. In this way the diagrams have the extra face validity of being figures already in the public domain as representing chemical species.

In fact two separate decks of cards were prepared for the work: one based on texts designed for students taking chemistry prior to A level (so that they might be expected to be familiar to students embarking on an A level course) and a second deck from A level texts. A selection of triad elements from each of these decks is presented in appendices 17 and 18 respectively. (I will refer to the cumbersome 'triad elements' rather than the usual 'elements' to avoid possible confusion with ***chemical*** elements. For example, ***triad element*** 314 represents a molecule of the ***chemical element*** hydrogen.)

Diagrams from books were photocopied (at a suitable enlargement), trimmed, and attached to standard record cards (c.100 mm x 150 mm). Reference numbers were arbitrarily assigned to avoid using verbal labels that might be too leading or convoluted. Diagrams were selected to show a range of types of chemical species (molecules, atoms, ions, parts of lattices), representing a range of substances that should familiar to the students, in various forms of representation relating to different aspects of structure and associated properties.

In this way it was hoped that Fransella and Bannister's (1977, p.13) criteria for triad elements would be satisfied,

(a) the elements must be within the range of convenience of the constructs to be used.

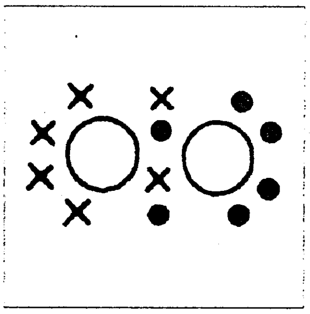
(b) the elements must be representative of the pool from which they are drawn.

The two decks of element cards were prepared using diagrams from

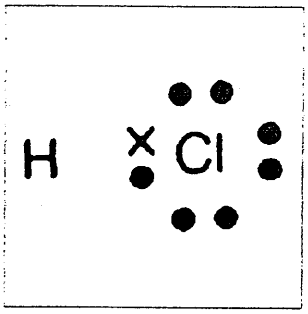
- books intended for pre-A level study (Freemantle and Tidy, 1983; Gallagher and Ingram, 1984; Garvie et al., 1979; Groves and Mansfield, 1981; Hughes, 1981; Jackson, 1984). A sample of these elements is presented in appendix 17.
- A level texts (Andrew and Rispoli, 1991; Hill and Holman, 1989; Liptrot, 1983; Waller, 1985). A sample of these elements is presented in appendix 18.

Both decks were extensive, intended to provide a large repertoire of triad elements that could be presented, and only a selection of figures were used on each occasion. The first deck was piloted with a student near the end of his first year of A level (colearner Edward), and then used with the second cohort of ten colearners (Jagdish, Kabul, Lovesh, Mike, Noor, Paminder, Quorat, Rhea, Tajinder and Umar) at the beginning of their course. Some of these students repeated the exercise later in their course. The second deck was tried out with an undergraduate chemistry student (who had previously been interviewed as an A level student, early in the interview study, colearner Brian) at the end of his first year at University, and was then introduced for use with some of the colearners during their second year of the course.

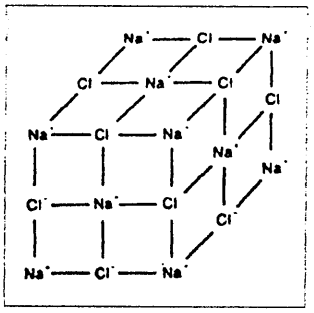
As an example of a triad of elements based on figures from pre-A level texts, consider 343, 454 and 553 (from appendix 17). This triad would be useful for exploring the discrimination between covalent and ionic bonding, and in particular to see if the triad elicits a construct relating to polar bonding.



triad element 343

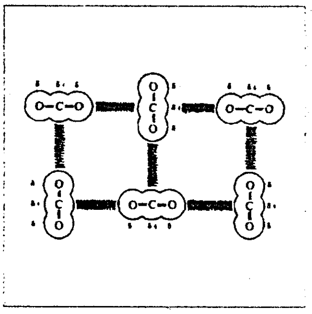


triad element 454

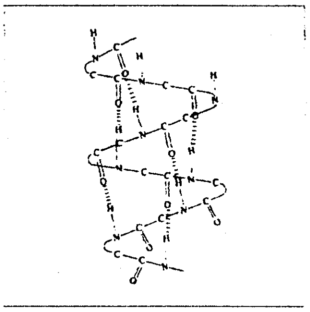


triad element 553

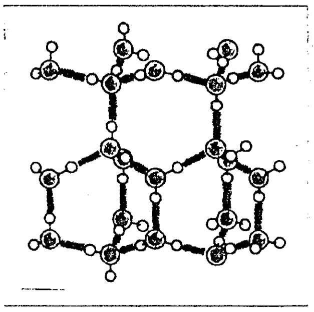
As an example of a triad of elements based on figures from A level texts, consider 180, 260 and 376 (from appendix 18). This triad would be useful for eliciting colearners' constructs of intermolecular bonding, for example discriminating between hydrogen bonds and other forms of dipole-dipole interactions.



triad element 180



triad element 260



triad element 376

Constraints of time - and colearners' concentration and interest - did not allow complete grids, where each ***triad element*** was considered against each ***construct*** elicited - to be formed. However, sometimes specific ***constructs*** from those elicited were selected and used to construe each ***triad element***. The choice of the particular constructs would be as a result of ***in situ*** hypothesis testing, when I wanted a clearer idea of what a particular colearner meant by the ***construct*** label offered.

§5.1.5: Procedures used in the Construct Repertory Test.

Two different approaches to selecting triads was used. At first the choice of triads to present was made ***in situ*** during the exercise. This allowed the researcher to try out combinations of triad elements that might be useful, and to discard some triad elements as less suitable (*e.g.* ambiguous) for future use. Just as important it allowed the exercise to be interactive, as the researcher reacts to the students' elicited constructs by offering the next triad. (It is possible that such an interactive approach may have also given colearners a stronger impression of their being 'right' answers that I was testing for. This is not considered to be a major problem as it is accepted that the colearners came to the research assuming that there were 'right' responses and that I (as their teacher) would know what these were.) After some experience of using the technique a standard set of triads was established for use with each pack. It is these two 'standard' sets of triads that are reproduced in appendices 17 and 18.

Both approaches have advantages. The less structured approach allows the researcher to undertake hypothesis testing (c.f. §4.2.1 and §4.2.3) about the students' ideas, and to follow up immediately responses that seem of particular interest. In a sense the process of the researcher offering a triad to the student, the student offering 'constructs' in response, and the researcher responding with a further triad gives the exercise the form of a conversation: something that has been recognised as inherent in grid work (Fransella and Bannister, 1977, p.4).

The advantage of having a standard set of triads is that comparisons become easier. Comparisons may be made between different students, or between the same students at different times during their course. Appendix 19 presents an example of a comparison between five colearners, in terms of the constructs elicited by one particular triad. Appendix 20 presents a comparison between the richness of the constructs elicited from two colearners at the start of their course. Appendix 21 presents a comparison of constructs elicited from a single colearner at different times, when construing the same triads. (The full list of constructs elicited during the research is provided in appendix 22).

§5.1.6: Colearner dialogues about chemistry.

As discussed in chapter 4, one technique used to supplement interviews was to record colearners discussing past examination questions (§4.8). The procedure followed was to pair two colearners and set them a task which required discussion. The discussion was recorded on cassette tape. I was present to set up the process, but then withdrew to the far side of the room, only intervening in order to answer procedural questions.

The pairing was based on a combination of which colearners wished to contribute in this way, when they - and the researcher, and a room - were available, and which students felt comfortable talking together in this way. It was only possible to collect a limited amount of data in this way, based on six sessions (as listed in appendix 1).

The tasks used were A level questions, about chemical bonding or bonding-related topics. This type of task was chosen as:

- It was felt that such past questions had validity as probes, being by definition set at Advanced Level, and pertaining to A level Chemistry.
- The tasks were seen as relevant by the student-colearners, who recognised that to be successful Advanced level students they would need to be able to answer such questions in ways that were judged (by an examiner ultimately) to be acceptable chemistry.
- The questions were structured, which meant that once the colearner pairs were set working they should need minimal input from the researcher.

The task that was set was to work *together* to answer the examination question. The students were told to attempt to agree the wording of their joint answer. The students themselves were left to decide how to go about answering the question, how much time to spend on various parts (no time limit was given), and to agree when they were finished. At the end of the session I would answer any of their queries, but as far as the research was concerned the product of the sessions was not so much the written answers produced, as the dialogue through which the answers were constructed.

§5.2: Details of analytical technique.

> "...written language consists of a system of signs that designate the sounds and words of spoken language, which, in turn, are signs for real entities and relations. Gradually this intermediate link, spoken language, disappears, and written language is converted into a system of signs that directly symbolize the entities and relations between them." (Vygotsky 1978, p.106.)
>
> "Vygotsky describes the process of learning written language as one where first-order symbols become second-order symbols (the child comes to discover that one can represent spoken language by written abstract symbolic signs), only later to become first-order symbols again at a higher level of psychological process..."
> (Newman and Holzman, 1993, p.104.)

§5.2.1: The problems of transcription.

The research interviews were of varying length, usually exceeding thirty minutes, and often more than an hour long. Interviews were tape recorded, so that the data collected is on cassette tape. (A back-up copy was made as soon as possible after the recording as security.) The recording loses much of the non-verbal interaction of the original transaction, but includes tonality, emphasis, hesitation and so forth as well as (vocalisation that may be interpreted as) words.

However, in order to analyse the interviews, it was necessary to transfer the data into some written form, that could more readily be edited, indexed, juxtaposed, re-sequenced, abstracted, compared, tested-against-conjecture, and so forth. Whilst the primary data for the study was the recordings (being the closest representation of the original conversations available), simply listening to the tapes *en masse* would not be a sufficient method of analysis, as the human brain cannot hold enough information in consciousness to consider all the issues relevant to the research. (Nevertheless, part of the analytical process is to listen to entire recordings to obtain overall impressions, and to confirm that the data-reduction process has not distorted the subject's meaning, c.f. §4.4.4.)

The process of transcription is a time-consuming and skilled operation. The researcher required approximately ten hours to produce an 'untidied' transcript of one hour of recording. (I use the term untidy - rather than 'rough' - to imply material that has been transcribed but not formatted in terms of utterance numbers and who is speaking, etc.)

Transcription is very much an interpretation process: it is not possible to produce a 'neutral' translation of the information on the tape (c.f. Stubbs, 1983, pp.227). The ears detect sound, but the brain infers words. Indeed after thirty or so years of practice of listening to speech my brain has developed its processing capacity to 'ignore' most of the words and to make conscious what experience has suggested is the likely meaning that the speaker intends: conscious conversation works at a fairly high semantic level. The transcriber has to try and work at a level closer to perception to produce a verbatim transcript. When checking early attempts at transcription I found that I had omitted ubiquitous "sort of"s which added nothing to meaning, and I had added 'missing' words, and 'corrected' word endings. Sometimes speech is indistinct on the tape, but one may not even realise this if the indistinct word(s) seem 'obvious' from the context (c.f. Stubbs, 1983, p.228). Although, on checking early versions of transcriptions I discovered many such 'errors', there were very few mis-transcriptions which altered the meaning of utterances. Indeed meaning that seemed quite clear when *listening* to the recordings could become less obvious in the written transcripts as finer precision was introduced. As Stubbs (1983, p.228) points out, the coarser, subconsciously edited, transcription may be closer to what the participants *experienced* during the original interview.

Having established that transcription is an interpretive process, the question of *should* a transcription be interpretive does not apply: instead the researcher has to make decisions about the *degree of interpretation* appropriate in the transcription stage of the data analysis (c.f. Stubbs, 1983, p.229). For example, if one was interested in a detailed discourse analysis there are notations to record changes in tonality during utterances (e.g. Coulthard, 1985). However, in the field of studies about the learning of science this has not usually been judged appropriate. Indeed classroom researchers Edwards and Mercer suggest that for those "interested in cognitive and educational processes, and particularly those whose research incorporates a developmental perspective, it is arguably [formal] discourse analysis which *scratches the surface*" (1987, p.10). In the present study I have also been influenced by Vygotsky's view that words make up the appropriate unit of analysis when studying conceptual development (§2.2.2).

Even ignoring formal discourse analysis I was left with a range of practical questions about the transcription process:

- Words such as 'there' and 'their' can not be distinguished by sound, but only by context - so should the transcription show '*there/their*'?
- To what extent is it important to include pauses?
- To what extent is it important to show mispronunciations of words?

In order to answer such questions I followed the principle that the researcher using interview data as a primary source of information needs to develop a transcript format that matches his or her *own purposes* in producing the transcripts.

I also needed to decide whether to transcribe complete recordings, or to be selective. Some interviews may not prove fruitful in answering research questions. For example in a longitudinal study some subjects may leave the cohort part-way through. Interviews with these subjects may ultimately contribute little to the enquiry, but it will not be known in advance which subjects may be lost, and some level of analysis will be required in preparation for any subsequent interviews with these subjects. Some subjects may tend to move the discussion into areas that are not directly relevant to the enquiry. The interviewer has the 'power' to prevent this, but may deliberately allow the respondent to follow her own trains of thought, as the interviewer does not know in advance what may be relevant in the mind of the respondent. If the discussion reveals an idiosyncratic connection this may be a significant aspect of the student's cognitive structure. If not, the only thing lost is time and tape (as all interviewers know - time and tape wait for no one), but little may be gained by transcribing this section of recording.

To summarise:

- transcription is a lengthy and difficult process, but was an essential treatment for some of the interview data;
- a style of transcription format needed to be developed to reflect the purpose(s) of the analysis;
- some recordings, and some parts of other recordings, may not require transcription; but
- it was not possible to decide what to transcribe until late in the enquiry; and
- some level of analysis was needed *during* data collection to 'feedback' into subsequent interviews.

The conclusion from these points was that during the enquiry

a) a format for transcriptions should be developed, and tested for its utility in (i) drawing conclusions, (ii) providing evidence to support results;

b) an on-going mode of data analysis is required that (i) is less time-consuming than transcription so it may readily be applied to entire recordings, but (ii) allows the abstraction of points of interest which can be followed up in subsequent interviews, and (iii) gives reference to the primary data (recordings) to allow ready access to points of interest for closer scrutiny.

The solution that emerged was that the data from the two main cohorts was treated differently. While the interviews of Annie, Brian, Carol and Debra were being undertaken, a limited amount of analysis was undertaken to inform subsequent interviews. Once these colearners had completed their course, their interviews were transcribed fully. By this time data was being collected from the other colearners, so the detailed analysis of the data from the first cohort took place as further data was being collected from other learners (c.f. §4.4.1, §4.4.4). A transcription procedure was developed and refined, and Annie's case study prepared.

Meanwhile, the interview data *then* being collected was initially analysed in less depth. All recordings were reviewed, and from each interview a protocol was produced which summarised the discussion. Initially this process involved a 'hard-copy' format using a series of hard-backed A4 notebooks, where alternate pages were used for the summary, and the facing pages used for notes. These protocols were coded (a list of codes used is given below), and indexed on a card-index system.

However, as the research proceeded I transferred the protocols to word-processing files on the computer, and started summarising subsequent interviews directly onto computer. This was done as far as possible in 'real time' on listening to the recording, using as much of the colearners' own language as possible. This provided sufficient written material to search for themes, and to apply initial codes.

As these protocols were word-processed, they were capable of being up-dated at any time. Indeed these protocols became working documents, and over a period of time sections of the summaries gradually became more detailed, and large sections were fully transcribed. For some interviews most of the data was eventually transcribed verbatim.

The use of the computer eventually made the card index system redundant as I was able to identify and access any word (either in a transcription, or my in coding or comments) on any file, using the software on the machine.

§5.2.2: Transcription.

Given that any transcription is an interpretation of the raw data the main decision to make when developing a transcription procedure is the degree of interpretation to be undertaken in producing the transcript (§5.5.1).

In developing the procedure used in this present study a number of trial transcriptions were undertaken. The transcripts were considered in the light of how readily they could be used in the next stage of analysis, and the perceived risk of any inaccuracies distorting such subsequent analysis. At this time a number of examples of transcript data quoted in the literature were considered for comparison purposes. Transcripts were modified, and re-formatted as a result of reflection on these issues.

The following transcription schedule was developed:

1. Sentences: although spoken language differs from the written word, a transcript is more sensible to readers if it follows the conventions of written language. It was decided that the use of capital letters, commas, and full stops was appropriate, although the 'sentences' produced may not reflect grammatical rules (Stubbs, 1983. p.35).
2. Spellings: words would be transcribed as accurately as possible, with 'their/there' (and other examples) being recorded as seemed appropriate from the context. This was extended to include 'N-A-plus' as "Na^+", and 's-p-three' as "sp^3" etc.
3. Hesitation: utterances such as "er", "uhm" etc. can provide information about hesitation and uncertainty, and would be transcribed as accurately as possible.
4. Emphasis: No effort would be made to systematically signify variations in tonality, but '?' and '!' would be used where considered justified. Particular emphasis placed on a word or phrase would be represented by <u>underlining</u>.
5. Utterance order: Speech would be listed in order of utterance, even if this meant 'sentence sharing' such that one speaker interjects into the other's pauses.
6. Simultaneous speech: Where speech overlapped this could be shown by the use of chevrons (>...> and <...<) to bracket together

the overlapping speech.

7. Speaker's moves: Each change of speaker would be represented by a new line. The speaker would be represented by an initial to the left of the speech.
8. Utterance numbers: For reference purposes 'utterance' numbers would be assigned, and shown at the far left of the page.
9. Silences: Pauses would be represented by •, with each • representing a pause of about 1 second. Short pauses within words would be represented by colons, e.g.: electro:negativity.
10. Brackets: Parentheses would be used:
    - [for additional information / interpretation added at transcription]
    - {for non-verbal sounds: coughing, laughter}
    - (for parts of speech apparently directed to the speaker his or herself)
11. Uncertain transcription: Where the recorded sound was indistinct and part of speech was not transcribed * would indicate the missing speech, with the number of * symbols representing (as far as possible) the missed syllables. Where a transcription was possible, but of uncertain precision, this would be represented by ~~striking the uncertain part through~~.

This transcription scheme involves a moderately high level of interpretation in that the speakers words are transcribed as questions, exclamations, etc. (see appendix 23 for a sample of transcript material). However the original data sources (the recordings) were available to be checked against the transcripts at any stage in subsequent analysis.

The system adopted for transcription actually provides a rendering of the recorded information that is closer to original data than may be appropriate when quoting to illustrate the model developed during the research, but I felt it was sensible to provide as much information in the transcripts as I was likely to need when interpreting extracts. It is simpler to subsequently edit over-elaborated transcript material, than to have to return to the right section of tape to fill-out sparse transcription. The editing process is discussed below (§5.3).

§5.2.3: Coding the interview data.

In order to analyse the data collected, especially with regard to the transcripts of interviews of an hour or so duration, it is necessary to use certain codes or categories to organise the vast amount of data. As discussed in chapter 4, in the grounded theory approach the categories are considered to *emerge* from the data, or - where the category used in one the researcher already had in mind - to be modified to provide an *emergent fit* with the data (§4.4.1, §4.4.4).

Initially the data was coded according to the aspects of the concept area being studied in terms of curriculum science: so when the first case study was prepared the data was considered under twelve headings:

- atomic structure
- definition of chemical bonding
- rationale and mechanism for bonding
- covalent bonding
- ionic bonding
- polar bonding
- metallic bonding
- multiple bonding
- delocalisation and resonance
- dative bonding
- hydrogen bonding
- van der Waals' forces

However, in interrogating the data there were a number of codes used that had arisen from my consideration of the literature:

- confusing the molecular and molar scales
- anthropomorphic language
- teleological explanation
- students' use of analogy

Other codes emerged from the data (§5.2.4), such as use of the notion of 'DEVIATION CHARGES' in Annie's case (§7.2.2), and the 'CONSERVATION OF FORCE' conception (§8.2.5).

During the interviewing of the first cohort (Annie, Brian, Carol and Debra) the following procedure was adopted. Loose leaf A4 file paper was used with a margin on either side of the paper. The reference number of the foci diagram was written in the left-hand margin, the respondents comments in the centre, and (at points of particular interest) the tape counter number was entered in the right-hand margin. This enable the appropriate section of the recording to be found for re-listening and quotations. These notes were used to prepare a list of questions to be asked in the subsequent interview.

For the second cohort (for colearners Jagdish, Kabul, Lovesh, Mike, Noor, Paminder, Quorat, Rhea, Tajinder and Umar) a hardback A4 note book was used for each colearner, with both tape counter number and diagram number on the left hand side. Only one side of the paper was used - the left hand page of each double spread - to allow plenty of space for notes to be made (interpretation, comparisons, ideas for follow-up, etc.) These notes would not necessarily be made concurrently, but could be added to when the protocols were re-visited.

§5.2.4: Using codes to index the interview data.

The process of analysing the interview data (through the use of transcripts or notes) requires the application of codes to 'fracture' (Glaser, 1978, p.55) the raw data.

The codes used may amount to no more than 'working hypotheses' of useful ways to consider the data, and over time the members of the set of categories emerging may be split, joined, discarded, supplanted, supplemented and so forth (§4.4.4). A most important requirement is that no categorisation should be exclusive - an utterance may represent several points of interest (i.e. it would not be appropriate the cut up a transcript/protocol and place segments into groupings.) An utterance may be cited as a referent in any number of categories, and segments of a transcript/protocol that are not classified at one time may be returned to later to be reconsidered in the light of new codes and categories.

Transcripts and protocols were studied, and codes generated liberally, and for each subject an alphabetical card index of citations was prepared. The use of index cards enabled ready additions, rearrangements etc. By coding data as the interviews continued I was able to develop my sensitivity to nuances of colearners' interview responses that might be relevant to emerging categories, and take opportunities to follow-up such leads during the interviews. At this stage of the analysis there were a large number of codes used: some common to a number of colearners, but others idiosyncratic. The codes used are listed in the box below.

The labels in the box represent the initial attempts to sort the data, and for this reason there is some overlap and duplication of these original codes. This is quite normal in this type of analysis as the initial codes are intended to relate to the data with ***minimal theoretical interpretation***. These codes influenced subsequent data collection, in particular by sensitising me to points of interest in my role as interviewer (c.f. Glaser, 1978, p.36). ***Some*** of the codes in the box are simply those used in coding the data from Annie in terms of aspects of the concept area (i.e. covalent boding, metallic bonding, see §5.2.3). However, a number of the codes being used at this stage developed into the categories around which the 'grounded theory', that is the model I present in chapter 6, emerged.

Codes used in analysis of interview data whilst data collection continued.

• analogy • anion size • anthropomorphism • antibonding orbitals • atomic structure • Aufbau • balanced forces • banana bonds • boiling temperature • bond angles • bond fission • bond order • bonding orbitals • bonding = touching • bridging/terminal • cause and effect • centripetal acceleration • changes of state • charge • charge/force • cohesion • compound/element • compound properties • compound/mixture • confused • contradiction • coordination number • core charge • Coulomb's law • counting twice • covalent bonding • criteria for bonding • criterion for bond type • dative bonding • delocalisation • diatomic = gas • dichotomy • dipoles • direction of bond • double bond • eccentric orbits • electricity • electrolytic conduction • electronegativity • electronic configuration • electrons • electron cloud • electron density • electron orbits • electron pairing • electron spin • electron wave • electrostatic attraction • electrostatic force • electrostatic framework • electrostatic interactions • element • energy levels • equilibrium • excited states • flat • force • force conserved • force fields • forgetting • Gestalt • giant molecular structure • geometry • gravity • guessing • heat • history conjecture • hydration • hybridisation • hydrogen bonding • idiosyncrasy • inductive effect • inference • ions • ion formation • ionic bonding • ionic charge • ionic molecule • ionic radius • ionic reactions • ionisation energies • just forces conjecture • lattice • learning conversations • logic • lone pairs • macro/μ • maximum speed • mechanism • melting • metacognition • metallic bonding • metallic structure • molecular energy • molecular ion • molecular orbital • molecules • multiple bonding • natural state • neutral charge • Newton 1 • Newton 3 • noble gas configuration • number of bonds • octet states • ownership • orbital • orbital labels • orbitals/reality • orbital shapes • oxidation numbers • partial charges • periodic table • polar bonding • polarisation • potential energy • projectile • proper bonds • pseudo-explanation • quantify/qualify • quantum rules • radii • random thought generator • rationale for bonding • reactivity • reality manifold • redox • rehybridisation • representation • representation/reality • resonance • screening effect • shape of molecule • shielding • shells • solid • solvation • spare • stable electronic configuration • stability • state • stoichiometry • surfaces • symmetry • tacit knowledge • tautology • teleology • V.S.E.P.R.T. • valence electrons • valency • valency conjecture • van der Waals' forces • variables • visualisation • waffling • 3-D • 3-D/2-D distortion • ∂-bond • π-bond • σ-bond

One example is ***anthropomorphism***. This category developed from a code that I had in mind before data analysis commenced (c.f. §3.1.4). Glaser has described how in such cases one needs to develop an "***emergent fit*** between the data and a preexistent category" (1978, p.4). In this case the initial code labelled all examples of anthropomorphism found. However as the analysis continued it was found that anthropomorphic language used to describe how and why chemical bonds formed took on a particular significance as part of ***octet thinking*** (§11.3). Not all the examples of anthropomorphic language as coded in the data were relevant to this particular category (which might be labelled 'anthropomorphism as a pseudo-explanation of the octet rule').

Similarly the code ***dichotomy*** originated from before the research commenced, and was central to my initial conceptualisation of the research focus. In my own teaching I had emphasised how the transition to A level required learners to switch from seeing the distinction *covalent-ionic* as a dichotomy, and considering it instead as a continuum. (This required them first to see the distinction metal-nonmetal as a continuum rather than a dichotomy.) In the research I discovered that the dichotomous perspective appeared to be part of a wider complex of related conceptions (§11.6).

By way of contrast the code *force conserved* was not based upon a code I brought to the data at the start of the research. Although my reading and professional experience meant I was aware of a range of alternative conceptions in mechanics and related areas, the 'conservation of force' conception discussed in this thesis (§10.5) has not to my knowledge been proposed as a specific alternative conception, although this research suggests it may be a commonly held idea (see appendix 3). This particular code was added quite late in the analysis, but once it emerged it was found to code for a number of instances in the data, and to inform the data collection (as it gave me a sensitivity to the possible significance of certain comments made by colearners, and therefore allowed me to test hypotheses about this notion being held, and thus elicit further examples).

An example of a code that developed by what Glaser refers to as 'refit' (1978, p.4) is *history conjecture*. Initially this referred to comments elicited in the context of ionic bonding, that is that an ionic bond would only be formed between ions that had transferred electrons - as if the electron or ions had some sort of memory of what had gone before (§11.4.2, and appendix 2). As analysis continued this developed into a category that included a wider range of data: so for example learners might suggest that on bond fission each atom gets its 'own electrons back'; another example where the *history* of the electron is endowed with some significance (§11.4.1).

§5.2.5: Citations to the data base.

In order to relate analysis back to the data in which it is grounded, a system of citations has been used. Each subject interviewed is referred to by an initial: A (Annie), B (Brian), etc. The tape recorded interviews are signified A1, A2 etc. (see appendix 1).

As the recorded data from Annie, Brian, Carol and Debra were completely transcribed, the source of an quotation or point of interest is cited in terms of the recording reference and transcript utterance number, e.g. A1.1, A1.2, etc.

As the protocols of the later interview included partial transcription, utterance numbers were not assigned (as these would have needed to be altered with each increment in the amount of the interview being transcribed). When the source is a recording which has not been fully transcribed, the citation is to the recording, and the tape counter number, e.g. J1.A076. (As counter readings are made intermittently this citation will have limited precision in relation to the tape.) It is possible to distinguish which form is being used, as the citations to partially transcribed recordings include a letter indicating the side of the cassette on which that part of the interview was recorded (i.e. A or B, or occasionally C or D where the interview was long enough to require a second cassette).

§5.2.6: Supplementary data.

The supplementary data was that collected outside of interview contexts. This included the construct repertory test (a clinical context, but different foci, and a different mode of elicitation); colearner dialogues (a clinical context, but minimal input from the researcher); and course work tasks (a more naturalistic context, and little or no scaffolding of the tasks by the researcher during their execution). Supplementary data was used in two ways: in what could be described as 'formative' and 'summative' modes.

The formative mode: During a sequence of interviews with a colearner, the data was interrogated to find particular points of interest. This information was used to suggest specific interview questions - sometimes explicitly referring to the evidence from the supplementary data source - to clarify and probe the colearner's thinking. Even where there was no specific use of this data, the process of working through the data could contribute to my background appreciation of the colearner's case (being part of the 'system input' for whatever subconscious processing my brain was undertaking - POST-INDUCTIVE RESONANCE, or 'integration' in McClintock's term, §4.2.1).

The summative mode: During the process of preparing case studies once a sequence of interviews was complete, the supplementary data was interrogated to find evidence that supported or challenged interpretations of interview data (bearing in mind that these data sources could not be considered 'independent' of the interviews, as they had been used to inform the interview questions). In other words, the supplementary data provided a form of *triangulation* for this interview-based study, but in terms of grounded theory's *constant comparison* approach (§4.4), rather than purely as a post hoc means of verification (Glaser and Strauss, 1967, pp.68-69, c.f. §4.4.4. It should be noted that recognising the subconscious processing that forms part of the analysis process (§4.2.1), and with one researcher collecting data of a qualitative nature, it would not have been possible to have genuinely ignored *slices of data* (§4.4.2) during the interviewing, even if this ***had*** been considered desirable).

Analysing construct repertory test data.

Some points of interest were clear during the process of data collection, and were recorded in field notes. The ethical stance taken in this research meant that I raised points that were considered to be particularly significant with colearners in the feedback at the end of the session. The data overall was subsequently examined.

Formative mode: To consider the data from Kelly's triads I would set out the triad of elements and work through the colearner's elicited constructs. I would note any constructs which suggested alternative conceptions, or ways of construing the elements which seemed to imply a different level of understanding to that expected. These points could be indexed, and could be followed up in later interviews.

As an example, consider colearner Noor. The construct repertory test suggested that she had alternative meanings for some basic chemical terms, including 'compound', 'molecule', 'ion' and 'element'. The nature of Noor's alternative nomenclature was such that the differences from standard usage were not readily apparent in interviews and written work: but became clear in the repertory test. This was because when Noor used these terms, she tended to use them 'appropriately' from a conventional viewpoint, but her own meanings meant she did ***not*** use the terms in other contexts where they would ***also*** be appropriate. Noor's meanings were restricted because she saw some of these categories as mutually exclusive (in P.C.T. terms, her constructs were *preemptive* rather than *constellatory*, Kelly, 1963 {1955}, p.153-4). This became clear in the repertory test as she had to construe the elements according to her personal construct system. Once elicited in this way Noor's meanings could be explored, tuition provided, and the development of her use of the terminology followed (see appendix 24).

Summative mode: the constructs elicited were interrogated to identify evidence to support or challenge interpretations from the interviews - for example elements that seemed to be 'misconstrued', or the absence of constructs that would be expected to be applied, but were not elicited, from particular triads. However, the failure to elicit a construct does not prove it is not part of the colearner's system: for example when asked about the absence of certain constructs from his construct repertory tests, colearner Tajinder reported that he considered certain discriminations to be too basic to be relevant to the research. For example, in appendix 21 constructs elicited from Tajinder from the same triads on two occasions are presented. In the case of the triad of elements 229, 307 and 349 Tajinder suggested four discriminations in October 1993, but only two in May 1994. Yet the constructs elicited on the later date were more sophisticated, and it would not be appropriate to suggest that Tajinder *no longer recognised* which of the triad elements *contained phosphorus* (for example). Rather he was presenting discriminations at a more abstract level, such as *whether d-orbitals were used in the hybridisation* (see appendix 21. This point relates to my comments about student seeing through the representations above, §5.1.3. Also relevant here is appendix 20 where it is tentatively suggested that Rhea's tendency to construe triad elements in terms of aspects of the form of representation - such as *got shading* - was an indication of her poor concept base in chemistry.)

Analysing concept map data.

Concept maps were sometimes set as a classwork exercise, to be carried out without notes or books. However, they were also set as homework, where students had access to such resources.

Formative mode: concept maps were checked and graded in my teacher role, but particular points of interest were noted for later follow up. These were generally of the nature of propositions that were either incorrect from the CURRICULUM SCIENCE viewpoint, or at least ambiguous or dubiously worded. These comments suggested possible alternative conceptions, and the colearners were asked about them in interviews.

Summative mode: in preparing case studies, the concept maps were able to provide an additional check on the interpretations from interview studies, e.g. the absence or application of a particular explanatory principle.

Analysing colearner dialogues.

The colearner dialogues were transcribed using the same format as the interviews (§5.2.2, see appendix 25 for a sample of the transcription). In an interview context I was able to structure questions to push colearners to the limits of their knowledge and understanding - in Vygotsky's terms to scaffold the dialogue to work in the colearner's Z.P.D (§2.2.2). In the colearner dialogues I made no input once the task was set-up and the students were working, unless I was asked for procedural directions. The dialogues suggested how far the colearners were able to push their thinking in the absence of teacher (researcher) input.

Once again, immediate feedback was given to the colearners for pedagogic purposes, and points of interest suggested lines of discussion for the interviews ('formative mode'), as well as providing another check on the interpretations of interviews when case studies were compiled.

Sentence sharing. In practice it was found that some of the data from dialogues was quite difficult to make use of in the ways intended, because much of the discourse was not identifiable to an individual learner. There was little difficulty in assigning *utterances* to the colearners, but much of the argument developed was clearly the result of the interchange, rather than the individuals. Even where one colearner seemed to be acting as the main source of ideas, and the other was mirroring these, the transcripts did not provide clear evidence for this. In many cases there was 'sentence sharing' where an individual statement was divided between the two students into several moves. Although this limited the use of the data as evidence for the thinking of an individual learner, it was suggestive of the extent to which the interviews I have carried out are also the product of a conversation.

In an interview context the normal conventions of speech are somewhat subverted by the researcher who is aware that in a sense the tape recorder is an audience: often full sentences are used, and clarifications - that would not normally be requested - are sought. However, in the colearner dialogues, the discourse is more akin to the normal patterns of speech where the assumed common knowledge provides a context, and a 'referential framework', allowing abbreviated communication, and where the dialogue requires instant response rather than deliberate considered statements (Edwards and Mercer, 1987, p.6; Vygotsky, 1986 {1934}, p.240, p.242).

Thus the conditions that lead to the 'sentence sharing' I observed. The purpose of 'sentence sharing' may be to check common understanding by the participants: Stubbs points out that completion of another's utterance is a demonstration of having understood (1983, p.22, c.f. §2.2.3 and Edwards and Mercer, 1987, p.141). In the present study this checking process may be seen to operate when the interjection made by one of the colearners is not consistent with the expectation of the other - on occasions such discrepancies were quickly overcome by one of the participants 'changing tack'.

Analysing other supplementary data.

Copies of some test scripts and other work undertaken by colearners as part of their course were kept on file. Again where there were specific points judged to be of particular interest that arose from this material, these points would be used to inform the agenda for interviews. The material was also available to be used as a check against interpretations made in writing up case studies.

§5.3: Compiling the case studies: using a journalistic style.

> "The analysis of an interview begins with two assumptions: (1) children answer honestly and (2) answers are consistent with personal meanings of concepts."
>
> (Ault, Novak and Gowin, 1984, p.446.)

Guba (1978) has suggested 'journalism' as an appropriate model for naturalistic research, where "*truth* can be elicited from partial, and even reluctant sources by processes of cross-checking triangulation, and re-cycling until convergence is achieved" (Guba, 1978, quoted in Gilbert and Pope, 1986b, p.42).

In preparing the case study of Annie, from the pilot study, I used a 'journalistic' approach to writing up the case (see §7.3). Having transcribed the interviews, and re-organised the data in terms of categories, I wrote up the case study to have a high level of readability by editing the evidence to give as far as possible a narrative form. (My interpretation of) Annie's thinking has been illustrated in her own words, but parts of utterances have been selected and spliced together to provide narrative, in the same way that a journalist might edit an interview for broadcast news (see appendix 26).

A deliberate decision to edit in this way places a responsibility on the researcher to ensure that increased readability is not attained at the cost of misrepresenting the full data. All citations from transcripts, short of publishing full texts, involve some degree of editing, and lose some of the information in the original tapes. In the case studies discussed in chapters 7 and 8 there is a high level of editing, and the reader should be aware of the scope for researcher bias and misinterpretation.

Despite these dangers it is accepted that such an approach is appropriate in writing up findings from a study such as this. So Sherman (1993) points out that qualitative research "has to make its case, in part, through literary persuasion" (p.233), and Sarup (1993) warns the users of such reports that "narrative, just by being narrative, always demands interpretation" (p.178).

In the previous chapter there was reference to Pope and Denicolo's (1986) discussion of *the researcher's dilemma* (§4.4.5). I have attempted to follow their maxim that "authenticity must be tempered with utility" (p.156.) To ensure ***utility*** my data chapters (7-11) have been written with an emphasis on providing a narrative to lead my readers through the substantive points. To ensure ***authenticity*** I have included in the appendices illustrations of the process of data reduction, and a range of verbatim evidence to exemplify and support my interpretations.

§5.4: Developing the model of progression of learning about bonding.

As explained earlier in this chapter (§5.2.3), the case study of Annie (discussed in chapter 7) was initiated by coding based upon my analysis of the concept area. As analysis proceeded with data from other learners a large number of codes of various types were used (§5.2.4).

Once data collection form the main cohort of colearners was completed, the data from all but one of the learners were put aside. Tajinder was selected as a suitable case for in-depth study as he had provided the greatest amount of data. For a period of some months this data was worked into a case study, without *direct* reference to the data from other learners - although of course the codes used to initially organise the data had originated in the earlier on-going analysis that had taken place during data collection (§4.4).

In order to work the data from Tajinder into a case study a multi-stage process was adopted:

- Each of the 23 interviews were summarised to produce a more manageable data source. This involved a great deal of editing, as described above (see appendix 27).
- A chronological case study document was compiled from the summaries, plus points from supplementary data that was considered significant. For the case study document the material from the interview summaries were reorganised thematically (see appendix 27).
- The main themes from within the case study document were identified, and Tajinder's case was written up around these to form the basis of chapter 8. At this point interpretations were checked back against the original protocols, extra transcription was undertaken where necessary, and suitable verbatim quotations were selected to illustrate the case.

The preparation of this case provided an outline model for organising the data from other cases. This was tested by preparing cases from the data from Brian, Carol, Debra, Jagdish and Kabul, based around this structure.

As a result of this process, the model was refined. The data from the other colearners (Edward, Lovesh, Mike, Noor, Paminder, Quorat, Rhea and Umar) were then interrogated and organised according to the model - again involving some refinement of the categories used in the model.

The incidental data collected from other learners was next considered in the light of the model. By this stage a model had been developed which seemed to explain a good deal of the original data. This version of the model was written up in chapter 6, and them the three main aspects of the model were described and illustrated in chapters 9, 10 and 11.

Chapter 6.

An outline of the findings of the study.

§6.0: The purpose and structure of this chapter.

The findings of this research project are presented in the following five chapters. The present chapter is intended to act as an *advance organiser* to give the reader an overview of the material to follow.

The idea of progression - that has earlier been met in chapter 1 - is considered in relationship to the examination syllabus that the learners were following (§6.1). Two particular features are highlighted, that learners need to develop an understanding of bonding in electrostatic terms (§6.1.1), and that they must acquire new concepts relating to quantization: concepts such as orbital, energy level and electron spin (§6.1.2). The two case studies presented in chapters 7 and 8 are then previewed in the light of this perspective (§6.1.3).

In chapter 1 the notion of LEARNING IMPEDIMENTS was introduced. In this chapter it is suggested that the lack of appropriate experience or background knowledge makes quantization notions difficult to learn - an example of a NULL LEARNING IMPEDIMENT (§6.2.1). It is also suggested that progression in understanding chemical bonding is affected by SUBSTANTIVE LEARNING IMPEDIMENTS, and in particular alternative conceptions of electrostatics (§6.2.2), and a common alternative rationale used by students to explain bonding (§6.2.3).

§6.1: The notion of 'progression' as it relates to the findings of this research.

In chapter 1, the notion of progression was discussed in terms of learners developing their conceptual toolbox (§1.7.2) to acquire the manifold models of chemistry (§1.7.1), and to overcome learning impediments (§1.7.3). In chapter 2 the constructivist approach to learning was considered (§2.1), as well as the notion that learners may be considered to undertake a cognitive apprenticeship (§2.8.5).

As the learners discussed in this thesis were enrolled on an examination course in chemistry the notion of their progression in understanding chemistry is related to the stipulations of the appropriate examination syllabus. The discussion will refer to the requirements of the Advanced Level Chemistry syllabus of the Associated Examining Board (syllabus number 0654). As the largest cohort of students interviewed took the examination in 1994, it is this edition of the syllabus - published in 1992 - which is quoted (A.E.B., 1992), and from which the key section has been reproduced in appendix 6.

Progression will therefore be understood in terms of the demands of this syllabus in relation to the level of understanding demonstrated by the learners before they were taught the relevant sections of the syllabus.

In this research it was found that at the beginning of an A level course learners tended to have simple models of the ionic and covalent classes of chemical bond (e.g. §11.6.1). Learners might also be aware that 'metallic' is also a category of chemical bond, but usually without knowing much more than it is bonding found in metals. The models of bonding that learners discussed at the beginning of their courses were based around the *octet rule as an explanatory principle* (§11.0, §11.2). These models gave little scope for the learners to develop the new categories of bonding required by their syllabus, and to develop the deeper understanding of bonding expected at this level.

§6.1.1: The adoption of Coulombic electrostatics.

The examination syllabus followed required students to know about hydrogen bonding, and the Van der Waals' forces "responsible for bonding in molecular crystals" (A.E.B., 1992, p.4). These types of bond can not be explained from the explanatory principles elicited from the colearners when they started the course. An understanding of these categories of bond depended upon the adoption of *electrostatic forces as an explanatory principle*.

The syllabus required students to understand ionic bond formation in terms of "ionisation energy, electron affinity and lattice energy", and required students to be able to demonstrate "a qualitative appreciation of the effects of ionic charge and ionic radius on the magnitude of lattice energy for simple crystals" (A.E.B., 1992, p.3), both of which required students to progress beyond the model of the ionic bond they had brought from earlier studies. Again the adoption of *electrostatic forces as an explanatory principle* was needed for learners to develop their understanding according to syllabus principles.

The syllabus also included a paragraph concerning polar bonding, and related concepts,

> "Bond polarity, electronegativity and inductive effect. Homolytic and heterolytic fission. Nucleophilic and electrophilic attack respectively, on positive and negative centres in molecules."
> (A.E.B., 1992, p.4.)

This was another area where learners could make little sense of the material from within their existing models of chemical bonds, and had to adopt *explanations in terms of electrostatic forces*.

The syllabus section on 'Structure and Bonding' (section 1, A.E.B., 1992, pp.3-4, see appendix 6) also included the requirements that students should study the shapes of simple molecules, and patterns of ionisation energies, both topics that required *the application of electrostatic principles*.

My analysis of the syllabus content in the light of the data collected (and considered in the subsequent chapters) leads to the conclusion that

one aspect of progression in understanding chemical bonding depends upon the adoption of Coulombic electrostatics as an explanatory principle for bonding.

§6.1.2: The acquisition of novel concepts related to quantization.

In principle a full understanding of chemical bonding at A level would be expected to include an appreciation of the concepts of atomic and molecular orbitals. The examination syllabus section on bonding and structure (A.E.B., 1992, pp.3-4) included references to "elementary treatment of quantum numbers and atomic orbitals", energy levels ("the line spectrum of atomic hydrogen as evidence for electron energy levels"), and sub-shells ("plot of standard molar first ionisation energies against atomic number to introduce sub-shells").

In addition the syllabus required candidates to be able to explain the shapes of molecules in terms of "repulsion between bonding and non-bonding electron pairs", and "the covalent bond considered as electron pairing or as the overlap of atomic orbitals". The notion of electron pairs is one which makes no sense from a purely electrostatic perspective, and requires the introduction of the concept of electron (quantum-mechanical) spin.

Learners were also required to know something of delocalised bonding (in benzene and metals), which again makes little sense in the absence of the molecular orbital concept.

These concepts (orbitals, quantum numbers, energy levels, sub-shells, electron pairs, delocalisation) are all notions that do not feature in pre-A level courses (i.e. the requirements for G.C.S.E. science or chemistry) and it would not be expected that students commencing A level should be familiar with them. The data collected in the present research supports this contention, and therefore leads to the conclusion that

> **one aspect of progression in understanding chemical bonding depends upon the acquisition of novel concepts related to quantization.**

§6.1.3: Progression in the case studies.

Models of cognitive change (§2.10) might also suggest that an analysis of progression in understanding chemical bonding could relate to the level of integration of electrostatic and quantum (i.e. orbital) concepts. However, I have discussed earlier how this is problematic as CURRICULUM SCIENCE does not present a coherent model of the chemical bond which readily integrates these two sets of ideas (§1.7.1). I have suggested, rather, that it might be appropriate to consider learning in terms of the analogy of acquiring a conceptual toolkit (§1.7.2). In the present research there was evidence that an apparent lack of coherence in the models being learnt did not seem to be necessarily problematic for learners, who were open to the manifold nature of the models of chemistry. This will be illustrated in some detail through the case of colearner Tajinder, who it will be shown was able to recognise that he selected from three competing explanatory principles: each of which he apparently viewed as a partial but incomplete truth (§8.4.5).

Indeed although analysis of the data was undertaken in terms of categories that separately considered aspects of what I will term 'electrostatic thinking' and 'orbital thinking', this scheme in part evolved from the analysis itself (through the principle of grounded theory, §4.4) and reflects the data.

In the subsequent chapters two case studies are used to illustrate progression. In the case of Annie (chapter 7) there is evidence of progression in terms of both the acquisition of new 'tools' being added to her conceptual 'tool box', and the increasing sophistication of her preexisting concepts (§7.1). However, Annie's case also demonstrates how progression may be limited by both aspects of a learner's existing cognitive structure (§7.21, §7.2.2), and by an ignorance of the tacitly assumed prerequisite electrostatic principles of A level chemistry course (§7.2.3, c.f. §3.1.3). The case also illustrates how an alternative conception (labelled

DEVIATION CHARGES) may become well established in cognitive structure and may prove stable despite being apparently incongruous with the material being presented to a learner (§7.2.2).

Annie's case also illustrates how a learner may apparently have available at one time two disparate explanatory schemes, and switch between them (§7.3). Early in her course Annie explained chemical bonding in terms of an explanatory principle based on full electron shells (labelled the STABLE SHELLS EXPLANATORY PRINCIPLE), and although she learnt to use an alternative principle based on electrostatic forces (the ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE) this did not immediately replace her existing explanatory principle.

This theme is explored further in the second case considered in depth, that of Tajinder (chapter 8). In Tajinder's case three alternative explanatory principles were elicited (§8.1). Like Annie, Tajinder used an explanatory principle based on the octet rule (labelled the OCTET RULE EXPLANATORY PRINCIPLE) as the basis for forming many explanations (§8.2.1). Again like Annie, he learnt to develop arguments based on a second explanatory principle derived from electrostatic considerations (which I have labelled the COULOMBIC FORCES EXPLANATORY PRINCIPLE, §8.3.1), and, once again like Annie, this supplemented rather than replaced his use of *octet thinking* (§8.4.4). As with Annie, Tajinder's application of accepted electrostatic principles to chemistry was impeded by an alternative conception (labelled CONSERVATION OF FORCE, §8.2.5). Tajinder also demonstrated the use of a third explanatory principle, based on the tendency for systems to evolve to minimum energy, which he used to complement his octet rule and Coulombic forces explanatory principles (labelled the MINIMUM ENERGY EXPLANATORY PRINCIPLE, §8.3.3).

In the discussion of this case it is shown how Tajinder's developing understanding of chemical bonding is related to his acquisition of the additional (i.e. COULOMBIC FORCES and MINIMUM ENERGY) explanatory principles to complement his original OCTET RULE EXPLANATORY PRINCIPLE (§8.4.3). Evidence is also presented to show how these alternative explanatory principles were concurrently available in Tajinder's cognitive structure over an extended period of time, giving him plural explanatory schemes to select from when discussing chemical bonding (§8.4.5).

In both cases then, progression, at least to the extent to which it was judged to have occurred, has been related to the acquisition of additional explanatory principles which supplemented, but during the period of the learners' courses did not replace, existing explanatory schemes

§6.2: Impediments to progression in understanding chemical bonding.

When the data collected for this study is considered in terms of the view of progression presented above, the major findings of this research may be summarised:

- Learners may experience difficulty in appreciating aspects of the 'orbital' concept used in chemistry.
- Learners exhibit beliefs about the interactions of charged particles which are inconsistent with Coulombic electrostatics, and may therefore act as a barrier (a SUBSTANTIVE LEARNING IMPEDIMENT, see chapter 1, §1.5.3) to the learning of CURRICULUM SCIENCE models.
- Learners exhibit beliefs constructed from an explanatory principle derived from the octet rule, which provides them with an alternative rationale for the formation of chemical bonding, before they are introduced to the model taught at A level.

Although these finding are to some extent illustrated through the discussions of the case studies of Annie and Tajinder presented in chapters 7 and 8, they are considered in depth in the thematic chapters 9, 10 and 11 respectively. Before the detailed evidence is considered in those chapters, the main features of each of these three findings will be outlined.

§6.2.1: Learners may experience difficulty in appreciating aspects of the 'orbital' concept used in chemistry.

In the present research it was found that some aspects of the orbital concept gave learners difficultly. The uncertainty about the meaning of electron spin (§9.2.6), and the identification of orbital probability envelopes with 'boundaries' (§9.2.4) were not judged to be be *serious* impediments to progress, but it was also found that

- learners commonly confused hybridised *atomic* orbitals with molecular orbitals (§9.3.2);
- had difficulty remembering the designation of atomic orbitals, and understanding the relationship between orbitals, sub-shells and energy levels (§9.2).

This theme is considered, in chapter 9, in less depth than the other two main findings considered below. In part this is because there is less data to discuss as *generally* the learners did not tend to answer questions in the interviews in terms of orbital concepts. However, I have also chosen to focus more on the other aspects of my results, as I believe they are of more significance. Learners tended to find orbital ideas abstract and unfamiliar, and - in the case of orbital labels - arbitrary. However learners seemed to experience little interference from existing knowledge when learning these ideas (that is they tend to experience NULL LEARNING IMPEDIMENTS, rather than SUBSTANTIVE LEARNING IMPEDIMENTS). By contrast the two other main findings concern competition between preexisting knowledge and the desired learning outcomes. It is these areas, where learning is heavily a matter of accommodation rather than just assimilation (§2.10.1), where I believe this study can offer insights of pedagogic significance (see chapter 12, §12.5).

§6.2.2: Learners exhibit beliefs about the interactions of charged particles which are inconsistent with Coulombic electrostatics.

As progression was found to be related to the adoption of electrostatic principles as the basis of explaining bonding phenomena, learners' notions about electrostatic forces are of central importance to the research.

It was found in this study that most of the chemistry learners interviewed exhibited notions about the interactions between charged particles which were inconsistent with CURRICULUM SCIENCE. This is discussed in detail in chapter 10. The following features were found amongst one or more of the colearners in the study,

- an interpretation of charge as a deviation from full electron shells, rather than a deviation from electrical neutrality (§7.2.2).
- forces were seen to act from one charged particle onto another, without reciprocity as required by Newton's third law (§10.4). The 'reaction' forces might be absent, considered as negligible, of the wrong sign (i.e. an attraction paired with a repulsion), or wrong magnitude (i.e. the greatest force acting on the smaller particle).
- systems were considered to be in equilibrium *without* forces being balanced; *or* to be non-equilibrium systems when forces *would* cancel (§10.3).
- nuclei were considered to give rise to a fixed amount of attraction - depending upon charge - which would be shared amongst the electrons available to receive it (§10.5).

These alternatives to conventional electrostatic principles were found to varying extents (for example the *deviation charges* notion was only elicited from Annie, but the notion of the effects of a charge being shared seemed to be common). Some learners were found to apply different variants of physical principles in contexts that were equivalent from a CURRICULUM SCIENCE perspective (c.f. §2.4.2). Similarly the meanings that learners appeared to give to words such as 'force' and 'attraction' did not always match the CURRICULUM SCIENCE definitions (c.f. §3.2.1).

§6.2.3: Learners exhibit beliefs constructed from an explanatory principle derived from the octet rule, which provide them with an alternative rationale for the formation of chemical bonding.

The adoption of electrostatic principles to explain bonding phenomena was found to be inhibited by colearners' preexisting notions. It was generally found that the colearners involved in the research commenced their A level studies with an existing rationale for chemical bonding which was based around a heuristic used in CURRICULUM SCIENCE called the 'octet rule'. This is discussed in more detail in chapter 11 (§11.0). Arguments constructed from this explanatory principle were elicited from learners at all stages of the A level course.

Colearners were found to use this principle,

- when they had no alternative rationale to explain why bonds formed;

but also,

- after they had been taught about bonding from an electrostatic perspective; and,
- after they had demonstrated they were able to apply arguments based on electrostatic principles;

and even

- to examples where the principle was invalid in its own terms.

By considering one case study in detail it will be demonstrated that colearner Tajinder was able to maintain and apply arguments based on several apparently inconsistent explanatory principles (§8.4.5). Tajinder was not only found to switch between arguments based on these different principles, but he also came to demonstrate an awareness and acceptance of the manifold nature of his mental models (a finding which it will be argued is particularly significant for the issue of the validity of 'multiple frameworks' as discussed earlier).

Although when considered in detail each colearner interviewed had a somewhat distinct set of notions about the explanatory power to be derived from the octet rule, it will be suggested that there are sufficient common aspects to justify the presentation of a model of *octet thinking.*

The basis of *octet thinking* is the FULL SHELLS EXPLANATORY PRINCIPLE

The FULL SHELLS EXPLANATORY PRINCIPLE

Atoms form bonds in order to achieve stable electronic configurations - variously referred to as octets, full outer shells or noble gas (electronic) configurations/structures.

This principle is the basis of a *complex* of related notions, such as,

- One way atoms can obtain full outer shells is to donate (give away) electrons (but they can only do this if another atom accepts them).
- One way atoms can obtain full outer shells is to accept (take) electrons form another atom.
- An ionic bond is (/is formed by) the transfer of electrons.
- If atoms overlap their outer shells then electrons in the overlap count towards the outer shells of both.
- An atom can therefore obtain an 'octet' by sharing electrons with another atom.
- A covalent bond is a pair of electrons shared between atoms.

A number of logically related features were identified in the research as being associated with 'octet thinking':

- an atomic ontology (§11.1)
- use of anthropomorphic language (§11.3)
- significance given to electronic history (§11.4)
- electrovalency as the determinant of the number of ionic bonds formed (§11.5)
- dichotomous classification of bonding (§11.6)
- distinguishing between bonds, and 'just forces' (§11.7)

Each of these features will be briefly described here, before being illustrated in more detail with evidence from the data base in chapter 11. In the discussion section (chapter 12) it will be suggested that it is appropriate to refer to this complex of ideas as a common ALTERNATIVE CONCEPTUAL FRAMEWORK (§12.3)

An atomic ontology: atoms as *the* units of matter.

The research suggests that atoms are ascribed a special ontological significance by learners, so that chemical systems tend to be conceptualised in terms of combinations of atoms, although this may not always be the most useful and appropriate approach. The notion of electrons *belonging* to atoms (see below) may be associated with this tendency to perceive discrete neutral atoms as some sort of 'natural' unit of matter.

The use of anthropomorphic language.

Whereas an *electrostatic explanatory principle* defines a mechanism for chemical processes to occur, i.e. electrostatic forces, the FULL SHELLS EXPLANATORY PRINCIPLE is not associated with any particular type of force. Colearners tended to give explanations based on this principle in language that was anthropomorphic, that is, atoms were spoken of *as if* they were sentient actors that had perceptions and desires, and were able to act accordingly. Such language may represent either anthropomorphic thinking on the part of the learner (thinking in terms of the atom being a sentient actor), or alternatively, a metaphorical description where the best way the learner can find to explain their thinking is to speak *as if* atoms were conscious agents (see §12.4.4).

The history conjecture: significance given to electronic history.

Another aspect of learners' thinking identified in the interviews was the implicit suggestion that the history on an electron is significant. This could be seen as closely related to the notion of electrons *belonging* to atoms: for if electrons belong to particular atoms then it might be important to identify which atom an electron came from, and therefore belonged to. One consequence of the history conjecture is an assumption that when a bond breaks atoms get 'their own electrons back'. The history conjecture may also lead to the ionic bond being defined in terms of the donation and acceptance of an electron between atoms, rather than an interaction between ions.

The valency conjecture: electrovalency as the determinant of the number of ionic bonds formed.

When an electron transfer event is seen as an integral part of the ionic bond, such that ionic bonds can only occur where there has been electron transfer, then the number of ionic bonds that an atom may form is determined by the number of electrons it will donate or accept in reaching an octet state, i.e. by the electrovalency, rather than by its coordination number in a structure.

A dichotomous classification ofbonding.

The FULL SHELLS EXPLANATORY PRINCIPLE readily accommodates covalent and ionic bonding, but the research suggest that learners cannot readily explain other bonding classes from this perspective. Therefore for a learner applying *octet thinking* anything that is recognised as bonding will tend to be classified in terms of the dichotomous classification ionic-covalent.

The just forces conjecture: distinguishing between bonds, and 'just forces'.

Some forms of interaction that are accepted as examples of chemical bonding within CURRICULUM SCIENCE may be labelled as 'just forces' by a student who understands bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE. For example interactions such as hydrogen bonding that do not lead to octet configurations may be discounted as bonds. When considering ionic materials, application of the VALENCY CONJECTURE will limit the number of bonds an ion is seen to form, and application of the HISTORY CONJECTURE will allow a specific interaction to be identified as *the* ionic bond so that the other interactions between counter ions may be considered to be just forces. Similarly, if a learner classifies bonds using the *covalent-ionic dichotomy*, then interactions that can not be understood as either covalent nor ionic may be discounted from consideration as 'proper' bonds.

Chapter 7.

Stability and lability in cognitive structure: the case of Annie.

§7.0: An overview of Annie's case.

Annie was one of the four colearners participating in the first stage of the interview study. She was interviewed on four occasions over a period of nearly 16 months: near the start of her second term of A level, near the end of her first year, and twice shortly before her A level examination (see appendix 1, §A1.1, for the schedule of interviews undertaken for the research). A case study was written around themes derived from the structure of the academic subject (see chapter 5, §5.3).

It was found that Annie's understanding of chemical bonding developed where her existing cognitive structure was labile enough for her to assimilate new ideas. However, the case study demonstrated that there were some aspects of Annie's cognitive structure that showed considerable stability, and where learning could only occur gradually.

It was also found that much of Annie's thinking about chemical bonding could be represented in terms of two complexes of ideas, one based around the notion of stable electron shells in atoms, and the other around electrostatic forces. These two ideas may be described as *explanatory principles* (§2.11.2) which acted as the foundation for much of Annie's thinking about chemical bonding. It is possible to interpret much of the development of Annie's understanding about chemical bonding in terms of these two explanatory principles, as over the four interviews the balance of Annie's explanations shifted from being largely based on her STABLE SHELLS EXPLANATORY PRINCIPLE (which was not valid from a CURRICULUM SCIENCE perspective), to being increasingly constructed in terms of her ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE (which reflected the principles and explanations of CURRICULUM SCIENCE).

§7.1: Lability in cognitive structure - evidence from the case study.

Annie's progression in understanding chemical bonding may be appreciated by considering some of the conceptual 'tools' (§1.7.2) that she developed or added to her conceptual tool-kit.

Covalent bonding. During the first interview Annie saw covalent bonding as being the type of bonding between two non-metallic atoms ("covalent is a bond that is formed between non-metals", A1.71), whereas she seemed to consider that sharing electrons (*or* overlap, *or* combining of atoms) was a more general criterion for the chemical bond (A1.134, 242, 354, 426 and 436).

127 I: ... are there any bonds in that diagram do you think?
128 A: Yes.
129 I: How many?
130 A: Four.
131 I: Four bonds, so we've got four bonds there. Erm, are the bonds actually shown?
132 A: Yeah.
133 I: So how are they represented on the diagram?
134 A: By the circles that overlap ...
A1

By the second interview her idea of covalent bonding was related to the sharing of electrons between similar atoms (A2.401), although she had little appreciation of the electrostatic nature of the bond. At the start of the fourth interview however Annie was also able to explain how the atomic nuclei attract the bonding electrons due to electrostatic force (A4.10).

1 I: perhaps before we look at any pictures you might just tell me what you think a chemical bond is:
2 A: Chemical bond, erm, it's a link between two atoms, which can be of a various, various different types. But basically links two things together, by either combination, or just by, charge. ... just by force they're held together. Actual forces on the atoms.
...
10 A: 'Cause the electrons are sort of held in circuits, orbitals, because when they sort of combine together, they're sort of going around freely, so you've got all the forces, sort of just like they're being pulled in by the nucleus. Electrons are being pulled in, so you're, you've got sort of the nucleus pulling in, the electrons from the other, atom. So it helps them stay together.
11 I: What kind of forces are they?
12 A: Electrostatic.
A4

Metallic bonding. During the first interview Annie did not believe metals needed any bonding to hold together, as the atoms involved were of the same element (A1.297).

294 I: Do you think those atoms will hold together?
295 A: Yes.
296 I: Why do you think that is?
297 A: Because they're all the same sort.
298 I: Does that make them hold together?
299 A: Yeah.
300 I: Yeah? Do you think there is any kind of bonds between the atoms?
••••••••• [pause, c.9s]
301 A: No, because they're all the same and they don't need to be bonded.
A1

By the third interview she agreed there was a form of bonding, but as this did not involve atoms *combining* she seemed to rate this as a lesser form of bonding than covalent (A3.408, c.f. §11.7.2). In the final interview, although Annie still did not consider iron had "actual bonds" she was able to give a description of the "delocalised" electrons which were "like a sea" (A4.82).

81 I: What holds a metal together?
••••••••• [pause, c.9s]
82 A: Erm, you haven't got like actual bonds in metallic bonding, like you haven't got anything, literally going in or out of a, a, a metal, but you've got delocalised electrons going round, the metallic atoms. In a sort of like a sea. So they're, they're all sort of freely flowing around.
83 I: Why should that hold it together?
84 A: Because, sort of, erm, metals haven't got full, full outer shells, then by electrons moving around, they're, they're getting, er a full outer shell, but then they're sort of losing it, but then like the next one along will be receiving a full outer shell. So, you've also got charges, that are forces from the nucleus pulling, just attracting, atoms from out, or electrons from outside in. Erm,
••• [pause, c.3s]
A: but mainly due to, like delocalised electrons they can move about, so, then you've got forces keeping, keeping it all together.
A4

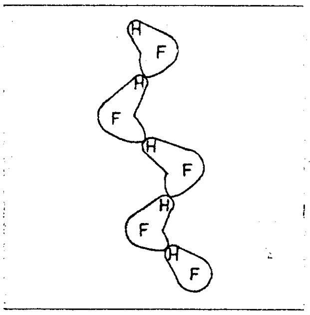
Canonical forms. Although in the second interview Annie thought that the canonical forms meant to represent molecular resonance implied discrete molecular structures (A2.299, c.f. §9.4), by the third interview she realised that they were just pictures that were meant to imply delocalisation, and that these chemical structures existed only in the minds of scientists (A3.269),

> "Yeah obviously the, ••• [pause, c.3s] sort of all the, all the carbons are going to be sort of have bonding power of four anyway. But sort of where they are actually bonded. It won't affect the structure or the way, in which sort of the, the compound reacts. But it just shows where the bonds could lie, but whether, *they don't really exist, it's sort of something that scientist has in their minds to show, to explain something.* So sort of three out of the six could be in one position or they could be, in the sort of reverse, although, sort of, I don't know if I should say *in nature, they don't actually perform that way.*"
> A3.269

Dative (co-ordinate) bonding. In the first interview Annie demonstrated no concept of dative bonding (A1.626), but in the second interview her ideas of bonding had become sophisticated enough for her to suggest that in some bonds both electrons come from the same atom - even though she used her own nomenclature for this (*chlorine bonds*, apparently by analogy with hydrogen bonds), rather than the accepted terms ***dative*** or ***coordinate*** (A2.368),

> "[chlorine]'s got a valency [sic] of seven. So, like it would need one electron, so some of the bonds, between like the aluminium and the chlorine, say one out of the four, may, might actually be like a chlorine-chlorine bond, but as the like electrons move round in a circuit anyway you wouldn't be able to trace them. So you can't definitely say."
> A2.368

Hydrogen bonding. Annie's comments about a diagram showing a chain of hydrogen fluoride molecules (focal figure 11) illustrate how her ideas on bonding became increasingly sophisticated during her A level course.



focal figure 11

At the time of the first interview she did not recognise the existence of any bonding between the molecules (A1.426).

421 I: Right, okay, do you want to have a look at ... picture 11,
A: yeah,
I: figure 11.
422 A: Oh gosh!
423 I: Any ideas about that?
424 A: {Laughs}
••••••• [pause, c.7s]
A: Not really, but must be a, sort of chain of, hydrogen fluoride molecules.
425 I: Chain of hydrogen fluoride molecules, okay yeah. Erm, is there any kind of bonding going on there?
426 A: There is within the, within the sort of shape of the H-F,
I: uh hm,
A: but when it meets up to like the H-F on the corners of the other shapes, they don't actually bond.
427 I: Okay, how many, how many different H-F molecules can you see there?
428 A: Five.
429 I: Five. And so how many chemical bonds are there in that diagram?
430 A: Five.
A1

In the second interview Annie was able to identify and locate the bond, and comment that it was a lot weaker than a *proper bond* (A2.268, c.f. §11.7.5),

265 I: Okay, you have a look at number 11? Any idea what type of bonds might be present there?
266 A: Hydrogen bonds.
267 I: Can you tell me where the hydrogen bonds are?
268 A: They're between where the, erm, on the diagram you've got like a, I don't know it's almost like a golf club shape
I: mm
A: where say the, the foot of the club hits the top of the other one, so, if you have H-F, then the, the next one along, the H and the F sort of holds them together. Or when you've got the proper bond of H-F, so the actual bond between the, the H and the F of the like neighbouring molecule, is a lot weaker, than the bond, actually in the substance.
269 I: Okay, you say this is a proper bond, this one, between the fluorine and the hydrogen
A: yeah
I: in here. What kind of bond is that?
270 A: It's erm, it's a, covalent bond ...
A2

It should be pointed out that Annie also wished to locate hydrogen bonds in several inappropriate contexts (A2.6, 59 and 81). This latter tendency seemed to have been overcome by the third interview as by then she was clear that hydrogen bonding could not occur in materials that did not contain hydrogen (A3.82). In addition she was able to explain that this type of bonding was an interaction between a hydrogen atom and a lone-pair of electrons on another atom (A3.84),

> "... obviously there's no hydrogen bonding involved [in focal figure 5], 'cause there's not any hydrogen there. Err, probably van der Waals forces, holding. ... Sort of van der Waals forces can occur, erm, and, I don't know how to put this. Sort of Van der Waals forces can occur to hold a molecule or atoms together as well as [sic] being sort of involved in bonding, whereas you know, if I was to say like it's hydrogen bonding then that's, involved in just like basically holding molecules near each other like in water the oxygen, lone pairs will attract, to the other hydrogen."
> A3.82

Van der Waals' forces. In the first interview Annie seemed to have no concept of van der Waals' forces, and instead invoked alternative, apparently *ad hoc*, reasons for molecular solids to hold together (A1.730),

727 I: Do you think that ... lump of iodine, would it stay together, or do you think it would fall apart?
728 A Stay together.
729 I: Is there something that actually holds it together?
730 A: Probably just *the forces of pressure* and, the, like *the charges from each thing would be stable*, so...
731 I: What the charges from, what?
732 A: From each molecule.
733 I: So each molecule, is stable,
A: yeah,
I: and you think that's what is holding it together?
734 A: Yeah.
735 I: Is there any force going from one molecule to another molecule?
736 A: There should be from the forces, *the forces from each iodine should have combined to stable-up*. But, there's probably other forces, which, erm, hold it together, in a solid or, so it wouldn't, wouldn't break off or anything.
737 I: Right, so there's forces holding the solid together,
A: yeah,
I: but would they be chemical bonds these forces, or?
738 A: No.
739 I: Not actual chemical, but some other type of force?
740 A: Yeah.
A1

By the later interviews she was clear that van der Waals' forces existed, and that they were weak interactions that were readily disrupted - although she imbued them with an ubiquitous nature and seemed to feel this was a 'catch-all' category that could be applied in a range of inappropriate contexts (A2.2, 93 and 125, A3.82 and 132). So the sodium atom was held together by "van der Waals forces ... weak forces, which pull towards the nucleus. Which are readily disrupted" (A2.2). In metallic iron (figure 6) "it's probably van der Waals forces, holding it together" (A2.93), although these forces are not the same as metallic bonding because "you can get van der Waals forces in, covalent things as well" (A2.107). Indeed Annie reported that lithium iodide (figure 8) is "ionically bonded, but the forces holding it together will be van der Waals I suppose" (A2.125).

§7.2: Stability in Annie's ideas of chemical bonding.

The examples given above all show how Annie made significant advances in understanding aspects of chemical bonding during the sixteen months of the case study. However, there were aspects of Annie's thinking where progression appeared to be impeded by the stability of parts of her cognitive structure.

§7.2.1: An example of how G.C.S.E. knowledge can interfere with A level learning: Bond polarity.

At G.C.S.E. level students are taught that the chemical elements may be conveniently classed as metals or non-metals (with a few 'semi-metals' or metalloids perhaps mentioned), and this dichotomy amongst elements leads to a dichotomous classification of bonding in compounds - covalent between non-metallic elements, and ionic between a metal and a non-metal (c.f. §11.6).

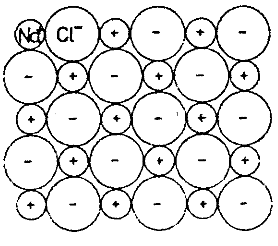
At A level both dichotomies give way to continua. The elements may be categorised on an electronegativity scale, and bonding may be polar. *Essentially covalent* compounds may exhibit some degree of ionic behaviour when there is a difference in electronegativity between the elements. Ions may be polarised and 'essentially ionic' substances can show some degree of covalent character.

Annie had clearly learnt that bonding between non-metals is covalent, and between a metal and non-metal is ionic (A1.71, 578, and 744). During her course Annie acquired a concept of bond polarity, which she correctly related to electronegativity (A4.162), and she was also able to discuss the use of the '∂+' and '∂-' symbols to indicate bond polarity, although she was not able to relate this to the notion of *partial charges* (A3.347). Despite this Annie continued to classify bonding as covalent or ionic, rather than polar ("that'll be, er, ionic ... for a start you've got, er metal and a non-metal. And you're going to get complete transfer, of electrons from the lithium to the, iodine atom" A4.284, c.f. §11.6.2). Her G.C.S.E. level knowledge appeared to act as an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5) to Annie's progression in thinking about bond polarity.

§7.2.2: An example of how an alternative conception can interfere with orthodox understanding: deviation charges.

In the first interview it became clear that Annie's interpretation of the symbols '+' and '-' (which are extensively used in chemistry to show ions) was different to the conventional interpretation. The orthodox meaning is of *electrostatic charges*, so that any species shown as '+' or '-' is ***not neutral***. Annie however had a totally different interpretation: that the symbols represented *deviations from noble gas electronic configurations* (A1.262).

Her interpretation led to her not recognising the presence of bonding in a diagram of sodium chloride, as the charge symbols implied *to her* that the species still had their atomic electronic configurations (A1.238, A3.30).



focal figure 5

One consequence of this was that although Annie interpreted the force between the sodium and chloride species as due to an attraction between opposite charges, for her this meant ***oppositely signed deviations from noble gas electronic configurations***: Na^+ being one electron in excess, and Cl^- being one electron deficient. As Annie's scheme included 'opposite' charges, and they still attracted, she was presumably still able to make sense of much that she heard and read, despite her alternative interpretation,

256 A: [focal figure 5] would probably get held together by just forces.
257 I: By forces. Any idea what kind of forces would hold it together?
258 A: Probably just the attraction.
259 I: Uh hm.
260 A: The attraction from the plus to the minus because like *chlorine's minus an electron* and *sodium is over an electron*. So they could just like hold them together, but not actually combine.
261 I: Right, chlorine's, so sodium's, say that about the electrons again.
262 A: *Sodium has like one extra electron, 'cause it has like an extra electron in its outer shell,*
I: uh huh,
A: and *chlorine has seven electrons in its outer shell so it's minus an electron* so by sort of exchanging,
I: huh hm,
A: the sodium combining with the chlorine just by force pulls they would hold together.
263 I: You say by exchanging, did you say?
264 A: Yeah by, well just the attraction in them.
A1

However, this alternative conception did have consequences for Annie's understanding of aspects of her course. One example is that although Annie acquired a reasonably orthodox understanding of the $\partial+$ and $\partial-$ symbols used to show bond polarity, she did not associate the term 'partial charge' with this symbolism, apparently unable to relate this to electronic configurations (A3.330).

Annie was able to 'balance' equations using her DEVIATION CHARGES, but as she was seeking full shells rather than neutrality the results could be quite different to the CURRICULUM SCIENCE answers: in the case of aluminium sulphate her stoichiometry was $(Al^{3+})_4(SO_4^{2-})_2$ rather than $(Al^{3+})_2(SO_4^{2-})_3$ (A2.226). Another consequence was that Annie was unsure whether Na^+Cl^- represented a compound or a mixture of elements, and confused the properties of sodium chloride, with those of its constituent elements (A3.174 and 192).

It is not possible from the case study to suggest the origin of Annie's alternative conception of charge. However it is clear that the alternative ***deviation*** interpretation was present in the first interview, whereas there was no evidence of the conventional 'non-neutral' interpretation. By the second interview (after formal teaching of the bonding topic) Annie had acquired the conventional interpretation, but this did not lead to the elimination of the ***deviation*** meaning. Indeed her alternative conception appeared to be applied spontaneously, whereas the conventional interpretation was used when questioning was targeted specifically at the electron configuration of ions compared to the atoms. Such cuing appeared to 'switch' Annie into applying her new conventional interpretation, although later she would resort to the alternative meaning.

Annie had presumably made sense of much that had been presented to her at G.C.S.E. and the start of her A level course using a complex of ideas constructed around DEVIATION CHARGES. Revisiting ionic bonding at A level and being taught contradictory ideas must have been confusing, so perhaps it is not surprising that some of Annie's utterances seemed to contain strands of both interpretations . By the fourth interview (after a 'tutorial' intervention) Annie was able to give a good account of ionic bonding in conventional terms, and to apply the conventional application of charge symbols. However, even at this stage there are vestiges of her earlier scheme apparent in the language used, such as referring to a chlorine atom as being "sort of minus an electron" and sodium being a "sort of positively charged, ion because of the, the extra electron" (A4.22 and 26). Like her dichotomy of bond types, Annie's notion of deviation charges delayed her progress, and thus acted as a SUBSTANTIAL LEARNING IMPEDIMENT (§1.5.3). (To be precise this would be another example of an EPISTEMOLOGICAL LEARNING IMPEDIMENT as it is "an aspect of cognitive structure *derived from* deliberate formal instruction" (§1.5.5). Presumably Annie was never ***taught*** the ***deviation*** interpretation of charge, but rather - in ignorance of electrostatic ideas - constructed a meaning to interpret her teachers' talk of positive and negative charges. However, a notion about deviations from noble gas electronic structures does not seem a likely ***intuitive*** idea, and is not sensibly classed as an ONTOLOGICAL LEARNING IMPEDIMENT. As explained in chapter

1, the discrimination between these two categories is intended to inform pedagogic practice, rather than make an absolute distinction. In this particular case it is perhaps *most* significant that *at the time* Annie first heard about atoms being ionised she did not have the appropriate prerequisite knowledge about electrical charge: that is she suffered an DEFICIENCY LEARNING IMPEDIMENT (§1.5.2), and as in fig 2.3(c) (§2.10.4) thus constructed her meaning in isolation from the CURRICULUM SCIENCE idea of charge.)

§7.2.3: An example of how the absence of assumed prerequisite knowledge can impede progression.

These two examples of stability - unhelpful stability from the point of view of on-going learning - were not the only ones that could have been drawn from the case study.

Another theme that could be explored was her interpretation of diagrams meant to represent electron clouds showing where electron density is most significant in bonds. Annie's understanding - or misunderstanding here - is related to her thinking in other areas. Because Annie did not understand what the diagrams were meant to show they did not help her appreciate polar bonding when it was illustrated through such representations. The reason Annie could maintain an alternative interpretation of the electron clouds as being *a type of force-field* (e.g. A1.305) was related to her ignorance of basic electrostatic ideas (she did not study A level physics, and had a DEFICIENCY LEARNING IMPEDIMENT (§1.5.2) in terms of expected prerequisite knowledge) that had her confuse the effects of charge - distorted electron clouds - with the fields themselves. (This is the same ignorance of fundamental physics that enabled her to believe that neutral atoms would attract if their had opposite DEVIATION CHARGES, whilst remaining skeptical of the attraction between species with orthodox charges.)

§7.3: Two explanatory principles used by Annie to make sense of chemical bonds.

A consideration of Annie's comments during the research interviews suggests that much of her thinking can be related to two explanatory principles that she applied in responding to questions about chemical bonding. I have labelled these principles the STABLE SHELLS EXPLANATORY PRINCIPLE, and the ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE.

The stable shells explanatory principle. This principle could be defined as *'chemical bonding is how atoms acquire stable shells'*. During the research interviews many utterances were elicited from Annie which may be interpreted as deriving from this principle (see §7.3.1).

In summary form this complex of ideas may be represented:

> Some sort of attraction is needed to hold atoms together: this can be of three forms, (a) the formation of chemical bonds by the joining of atoms *to form stable shells* through sharing of electrons, (b) the combining of atoms due to their [*deviation*] charges, that is the extra electrons, or the need for additional electrons *to form stable shells*, or (c) by other forces.
>
> (a) Chemical bonds are also called covalent bonds, and occur between non-metal atoms.
>
> (b) Atoms with matching [*deviation*] charges, that is metal atoms with non-metal atoms, may combine to form neutral molecules, and this is sometimes called ionic bonding.
>
> (c) The other forces will hold together atoms or molecules that are already stable and have no need to form bonds, or similarly charged metal atoms that are unable to achieve stable shells through combining or joining together. These forces are not proper bonds, and have various names such as metallic bonding, hydrogen bonding, and van der Waals forces.

The electrostatic forces explanatory principle. This principle could be defined as *'chemical bonding is due to the electrostatic force between nuclei and electrons'*. This perspective is closely related to the CURRICULUM SCIENCE model. During the research interviews many utterances were elicited from Annie which may be interpreted as deriving from this principle (see §7.3.2).

In summary form this complex of ideas may be represented:

> Opposite charges (positive and negative) attract due to electrostatic force. Similar charges repel.
>
> In an atom the positive charge in the nucleus leads to an electrostatic force which draws the electrons in, and holds the atom together. The strength of the force depends on how close the electrons are to the nucleus. The outer shell electron can not get too close as they are repelled by inner shell electrons.
>
> If atoms collide the charged sub-atomic particles will give rise to forces. Protons in one atom would repel protons in the other, and the electrons would also repel. The protons in one atom would attract the electrons from the other. This may lead to the atoms being held together, with electrons being pulled towards both nuclei, to give a molecule. The force may be greater from one nucleus, and sometimes an electron may be transferred to give ions, which will be held together by electrostatic force in ionic bonding.
>
> In metallic bonding there is a force from nuclei to the sea of electrons; in hydrogen bonding lone pairs of electrons attract hydrogen; van der Waals forces are due to the attraction between opposite charges; in solvation ions are attracted to different parts of the solvent molecule.

These two complexes may be illustrated in terms of the utterances elicited from Annie during the interviews. The notions presented (as the ***italicised*** sections §7.3.1 and §7.3.2) are - where not *verbatim* - in phrases close to Annie's own words. These composites are drawn from all four interviews, so that

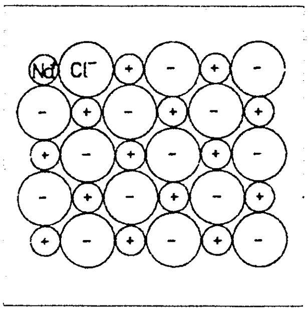
(i) the full set of ideas in the *complex* were not elicited from Annie at any one time;

(ii) during any one interview Annie presented aspects of both complexes.

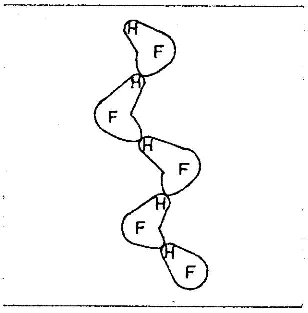
Citations are provided to the location of the utterances on which these complexes are based, within the interview transcripts. Although there is some evidence of both explanatory principles being used throughout the time she was participating in the research, it is also clear that in the first interview Annie's explanations of bonding were heavily based in the STABLE SHELLS EXPLANATORY PRINCIPLE, with the ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE only being invoked to prevent atoms falling apart. Over the four interviews this balance shifted so that by the last interview Annie gave for the research the ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE was much more in evidence, than the STABLE SHELLS EXPLANATORY PRINCIPLE

§7.3.1: Notions elicited from Annie, related to the stable shells explanatory principle.

Some sort of attraction is needed to hold atoms together, either the formation of chemical bonds, or the combining of atoms due to their charges. Bonding involves the joining of atoms which combine to form stable shells. Bonds are represented by circles that overlap (A1.134), and a diagram which does not show overlap does not represent bonding (A1.426, A1.436, A1.438). For example a diagram such as focal figure 5 which has Na^+ *and* Cl^- *just in rows, just shows atoms (A1.238) with no bonding (A1.240).*



focal figure 5



focal figure 11

Similarly there is no bonding between the molecules in the chain of HF molecules shown in focal figure 11 (A1.446). Chemical bonding involves the sharing of electrons, so the atoms have got two electrons between them, and they have each contributed one to the shell (A1.65), which is called a covalent bond (A1.69). Examples of this include the iodine molecule which holds together because of the sharing of electrons (A2.401); lithium combining with iodine to make a stable outer shell between the two atoms, by sharing electrons (A1.321); the bonds in tetrachloromethane which are covalent as the atoms share electrons to give them all full outer shells (A2.12); hydrogen atoms which combine to form a stable first shell (A1.59); and the bonds in the oxygen molecule which are covalent (A1.226) as each oxygen atom is giving two electrons so they can each form a shell of eight (A1.230).

By comparison, 'just combining' involves a matching-up of deviations from stable shells, that is when something with a positive charge (excess electrons) combines with something with a negative charge (deficient in electrons) to become neutral overall. For example Ca^{2+} *and* O^{2-} *would just combine because one is lacking two electrons and one has got two, and oxygen, which has a 2- charge, combines with two hydrogens which have a combined charge of 2+ (A3.227). In this context stability relates to electronic structure. For the first shell stable means two electrons, as when two hydrogen atoms are joined because they only have one electron in their first shell, so they combine to form a stable first shell (A1.59). For the second shell stable means eight electrons. Examples of this are oxygen atoms (in oxygen) which give two electrons to 'match-up' so they can form a shell of eight (A1.230), and in sodium when an electron is removed, and the eight electrons in the next quantum shell make the atom more stable than when it had one electron on its own (A4.76). This definition of stability* *encompasses both elements, so a hydrogen molecule has got two hydrogen atoms, to give an outer shell (A2.135), and compounds, where two or more different elements make up the full stable shell (A2.137).*

A full shell implies neutrality, so eight extra electrons would be 8+, which would become nought (A2.236), and would be a neutral charge (A2.234). Similarly if sodium and chlorine were bonded there would be an overall neutral charge, because of donation of electrons neither would then have a plus or minus charge. Other configurations are not stable, so for example hydrogen atoms are unstable because they've only got one electron (A1.77). Not having a stable shell has consequences. It gives rise to charges (which are deviations from a stable shell): hydrogen atoms are minus an electron (A3.150), although two hydrogen atoms would both have a plus charge as they have both got one electron in their outer shell (A4.162). Chlorine is minus an electron, where sodium is over an electron (A1.260), and is positively charged because of the extra electron (A4.26). Iodine has seven electrons in its outer shell so it has a negative charge (A2.109), and carbon atoms have a 4+ charge (A3.273). The species SO_4^{2-} *has two electrons missing off it (A2.170), that is, it is two electrons short (A2.176).*

Unstable electronic configurations give rise to forces, so two hydrogen atoms in a molecule would be held together by forces due to their lack of electrons and abundance of them (A1.307), and sodium and chlorine atoms are held together by the attraction from being one electron over, and one short (A1.279). This leads to electron transfer, so sodium loses its extra electron to gain a stable shell (A4.46). Unstable configurations also give rise to 'needs', as in the case of the hydrogen atom, which needs to combine so it can be more stable (A1.77). Species with stable outer shells may be held together, but by other forces, not by chemical bonds. For example, iodine molecules are held together (A1.728) though not by chemical bonds (A1.738) but by other forces (A1.736). Bonding is not needed to to hold the structure of sodium chloride together, just forces (A1.256), and Ca^{2+} *and* O^{2-} *would not need to form a bond (A1.754), but would just combine (A1.758) to make up full shells (A1.760).*

In a metal there are no actual bonds (A4.28), but the structure is held together: the atoms are not really sharing, and are not really combining, but they are held together, so there is something going on (A3.426), and although the atoms are similarly charged they do not repel each other (A3.404). For example there is no bonding in a piece of iron (A2.55), but it is held together by something, probably van der Waals' forces (A2.39). There are forces, as - due to delocalised electrons - an atom is getting a full outer shell, then losing it (A4.84), but this is not as definite as when electrons are completely transferred or shared, so there are not bonds in the sense of covalent or ionic (A4.90).

Electrons are held in place in the atom, which is connected to the set pattern of how many can go in each shell (A1.33).

§7.3.2: Notions elicited from Annie related to the electrostatic forces explanatory principle.

Opposite charges attract (A3.42), so where you have got positive and negative they are going to attract (A4.409). This is involved in holding an atom together: electrons do not fall out of atoms, due to the attraction from the protons (A1.43). The attraction is between the electron and the nucleus (A4.201), as protons and electrons have charge (A4.189). The protons in the nucleus have a plus charge (A3.8), and the protons in the nucleus draw the electrons in by electrostatic forces (A3.8). These electrostatic forces come out from the nucleus (A3.6). The larger the atom, the less power the nucleus has on the electrons (A3.8), whereas the closer the electrons are to the nucleus, the more force holds them in (A3.8).

The attraction of opposite charges can also lead to interactions between atoms, for example if two hydrogen atoms collide the proton from one atom could attract the electron from the other atom (A4.205). The attraction can hold atoms to one another, in molecules (A3.146), and remains even when the substance is vaporised (A3.150). This attraction occurs as the nucleus of one atom pulls in the electrons from the other atom (A4.10), with electrostatic force (A4.12), which may lead to a symmetrical arrangement, if the atoms have similar electronegativities (A4.162) or not, in which case ∂ symbols are applied. So in the hydrogen molecule, both nuclei are equally attracted to both electrons (A4.239), so the way the charge has been distributed around the molecule is fairly symmetrical (A4.162), as the distribution of the charge around the molecule has not been polarised (A4.162). However, the electrons in an O-H bond would be pulled towards the oxygen more than the hydrogen (A3.306), and so hydrogen would be ∂+ and oxygen would be ∂- (A3.347).

In metallic bonding there are delocalised electrons, like a sea, and there are forces from the nucleus pulling the electrons (A4.84). Hydrogen bonding is involved in holding molecules near each other (A3.84), as lone pairs of electrons attract to hydrogens, so in water oxygen lone pairs attract hydrogen in other molecules (A3.84). Van der Waals' forces occur to hold molecules or atoms together (A3.84), and are due to the attraction of opposite charges (A3.82).

The attraction of opposite charges can lead to the formation of ions, which are atoms that have become charged. '+' represents the electron that has been lost, giving the atom a positive charge, so that K^+ *is an ion (A2.143), a potassium atom that has lost an electron (A2.141), and in* Na^+ *the electron has somehow been removed (A3.64). Ions may be formed by electron transfer, where the nucleus of one atom has the power to draw electrons from another atom in (A4.30), where the force on the electron, is dragging it towards the nucleus (A4.30), as when an electron from sodium is pulled towards the chlorine. The attraction can hold ions to one another, which is called ionic bonding (A3.184), as in the chemical bonding between sodium and chlorine (A4.182). This is due to electrostatic force (A4.318), so for example there is an* *electrostatic force from a potassium ion to a fluoride ion (A4.316), and an electrostatic force from the fluoride ion to the potassium ion (A4.320).*

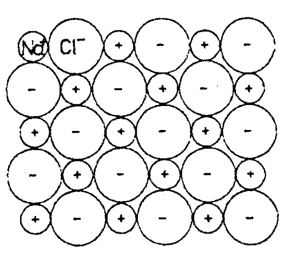
The attraction between charges can lead to solvation. A polar solvent will solvate ions, when the positive ions go to one part of the solvent molecule, and the negative ions to another (A3.221).

Similar charges repel (A4.517). This has consequences for atomic structure, as it prevents outer shell electrons getting too close to the core (A4.517). This also leads to interactions between atoms, so if two hydrogen atoms collided the two protons, and the two electrons, would repel each other (A4.207).

§7.4: The case in relation to the main themes of the research findings.

Annie's case may be used to illustrate major themes which emerged during this research project, and which are illustrated further in chapters 9, 10 and 11.

- *Annie's progression depended upon the adoption of Coulombic electrostatics as an explanatory principle for bonding.* An example of how Annie's developing understanding of chemical bonding depended upon her adoption of conventional electrostatics was her acquisition of the concept of 'hydrogen bond'. Annie progressed from ignorance of this category of bond (§7.3.1), to awareness, to being able to explain it in the case of water as due to an attraction between a lone pair on oxygen, and the hydrogen in another molecule (§7.3.2). This progress may be understood to be related to the adoption of the ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE as the basis for understanding chemical bonding.



focal figure 5

Another example would be Annie's understanding of the ionic bond. Her initial interpretation of focal figure 5 (a cross section of an NaCl ionic lattice) was that there was no bonding present, and the Na^+ and Cl^- species were atoms, held together "just by force pulls" (A1.262). Although Annie did not completely adopt an electrostatic model of ionic bonding, by the end of the course she recognised ions, and explained that in the case of potassium and bromine, the potassium would become an ion when it has "got rid of an electron" (A4.405), and there would be "a bromine minus ion from gaining an electron" (A4.407), so "because you've got positive-negative ... they're going to attract" (A4.409). In the next chapter it will be shown that colearner Tajinder's developing understanding of chemical bonding also involved his *adoption of an electrostatic explanatory principle* (§8.4.3).

- *Annie experienced difficulty in appreciating aspects of the 'orbital' concept used in chemistry.* Annie used the terms 'shell' (and 'quantum shell'), 'orbitals' and 'energy levels', but did not seem to clearly discriminate between them (see §9.2.1). Similar problems were experienced by other colearners (§9.2). Annie originally understood the electron density envelopes drawn to represent molecular orbitals as a type of force-field (c.f. §9.2.1).

- *Annie exhibited beliefs about the interactions of charged particles which are inconsistent with Coulombic electrostatics.* Annie's notion of (what I have labelled) DEVIATION CHARGES was an extreme example of alternative notions about electrostatics, as she actually considered electronic configurations themselves to give rise to a force. Annie's misunderstanding of the meaning of the symbols '+' and '-' impeded her progress throughout the course, and at least vestiges of this way of thinking were present in the fourth interview, shortly before her final examination, despite a tutorial intervention after the third interview (§7.2.2).

Annie also spoke of forces in ways that were not in keeping with the CURRICULUM SCIENCE approach. She demonstrated a belief in a nucleus giving rise to a certain amount of pulling power, rather than construe the force as due to the interaction between charged particles (A4.514, see §10.5.1). Similar findings from other learners will be discussed in chapter 10 (§10.5). So Annie did not understand the reciprocal nature of electrostatic forces, and suggested that when a potassium ion was adjacent to a fluoride ion, the fluoride exerted a larger force on the potassium than vice versa (A4.245, see appendix 31, §A31.4.12). Annie thought a nucleus attracted an electron more than vice versa (and she had a similar perception of the gravitational interaction between the sun and earth). Similar findings from other learners will be discussed in chapter 10 (§10.4.4).

- *Annie exhibited beliefs constructed from an explanatory principle derived from the octet* *rule*. Annie's STABLE SHELLS EXPLANATORY PRINCIPLE was presented above (§7.3), as was the complex of associated notions elicited from Annie during the research (§7.3.1). As this complex demonstrates, the STABLE SHELLS EXPLANATORY PRINCIPLE was Annie's principal starting point for discussing chemical bonding during the first year of her A level course, and remained a significant basis for her explanations through her second year. A similar explanatory principle was elicited from colearner Tajinder as will be discussed in the next chapter (§8.2.1). Indeed, an explanatory principle of this type seemed to be ubiquitous amongst the colearners in this study (§11.0).

Various aspects of Annie's *octet thinking* will be shown to be reflected in the data collected from other learners. Particular points to note in this respect are:

- the rationale for bonding: atoms share electrons to obtain full outer shells (§11.1.5);
- anthropomorphic language: atoms *give*, and *share*, electrons, and *need* to combine to become more stable (§11.3);
- a molecular interpretation of the ionic bond: although Annie's notion of DEVIATION CHARGES led to her construing figures representing ionic materials as being *pre-bonded*, she thought that actual sodium chloride contained molecules (§11.4.3). When thinking about the ionic bond Annie seemed to focus on the act of electron transfer, as if that *was* the bond (§11.4.2).
- a dichotomous classification of bonding: with models of covalent bonding (sharing electrons by overlapping) and ionic bonding (combining by matching up deviation charges) that do not readily admit of intermediate cases (§11.6).
- bonding is distinguished from other forces: so that where an interaction is not conceptualised in terms of obtaining an stable configuration, it is not classed as a bond (§11.7).

Chapter 8.

Alternative explanatory principles: the case of Tajinder.

§8.0: The structure of the chapter.

Tajinder was one of the colearners in the main cohort (1992-4) of chemistry students who participated in the study. Tajinder valued the experience of taking part in the research to such an extent that he requested additional sessions, and he was interviewed on over twenty occasions (see appendix 1, §A1.1), providing by far the most data of any of the colearners.

This chapter deals exclusively with Tajinder's case. It commences (§8.1) with a general overview of the case, and introduces the three *explanatory principles* that are considered to be central to Tajinder's thinking about chemical bonding. Then there is a consideration of Tajinder's understanding of the topic at the start of his course (§8.2), looking in particular at the OCTET RULE EXPLANATORY PRINCIPLE that was the basis of his thinking about bonding at that time, and his understanding of forces. This provides the foundation for considering how Tajinder developed two new explanatory principles related to forces and energy during his course (§8.3).

Progression in Tajinder's understanding of chemical bonding is then discussed by considering the new conceptual tools he has acquired, and the increase in the range of phenomena he subsumes under his construct of *chemical bonding* (§8.4). It is argued in this section that Tajinder's progression was closely linked to his new explanatory principles, especially his COULOMBIC FORCES EXPLANATORY PRINCIPLE (§8.4.3). However it is also pointed out that these *supplemented* rather than *replaced* his preexisting OCTET RULE EXPLANATORY PRINCIPLE, which appeared to be deeply ingrained in his thinking (§8.4.4). So at the end of Tajinder's course he was working with three effectively distinct principles for explaining the same basic set of phenomena. Through the interviews Tajinder became aware of the pluralism in his thinking, and seemed quite happy to accept that his understanding of chemical bonding was based on a set of models, each of which he considered useful for *some* of the explanations he was required to give in chemistry (§8.4.5).

Tajinder's conscious awareness and acceptance of his pluralistic approach to explaining chemistry is seen as significant because of (i) the comments made about the fragmented nature of chemical knowledge in chapter 1 (§1.7.1); (ii) its relevance to the debate over the reality of students holding ***multiple frameworks*** considered in chapter 2 (§2.5.2); and (iii) its relevance to the question raised from a Piagetian perspective over whether adolescent students are capable of ***post-formal thinking*** (§2.2.1, although Tajinder was clearly an intelligent student and can not be taken as typical of 16-18 year olds).

The case study in this chapter is the result of many stages of analysis, and the interpretations presented are therefore many steps removed from the original data (as discussed in chapter 5, §5.3 and §5,4; see appendix 27 for an overview of the analysis and sample extracts from three intermediate stages in preparing the case study). It was suggested earlier that authenticity in interpretive research rested in part on the presentation of sufficient verbatim evidence to support the interpretations (§4.4.1, §4.4.5). Limitations of space, and considerations of readability, however lead to this chapter being a narrative digest of my findings (c.f. Pope and Denicolo's *researcher's dilemma*, §4.4.5). However, this chapter is supported by two appendices (appendices 28 and 29) which present many extracts from the original data base to support my findings.

Appendix 28 considers how Tajinder's progression in understanding chemical bonding may be linked to his acquiring and adopting an electrostatic explanatory scheme. That is, that Tajinder commenced A level chemistry explaining chemical bonding through his OCTET RULE EXPLANATORY PRINCIPLE, but in order to make progress he had to learn to use an alternative basis for his explanations, the COULOMBIC FORCES EXPLANATORY PRINCIPLE. It is proposed that to a great extent Tajinder's developing understanding of chemical bond may be seen as a transition from relying almost exclusively on the former, to increasingly using the latter when thinking about chemistry.

Appendix 29 provides evidence to support my findings that Tajinder never completely ***replaced*** his original OCTET RULE EXPLANATORY PRINCIPLE with his new COULOMBIC FORCES EXPLANATORY PRINCIPLE, and that he never integrated his ideas about systems evolving to minimum energy with the effects of electrostatic forces. This appendix then looks in detail at the pluralistic nature of Tajinder's explanations of chemical bonding.

Evidence from this case is also incorporated in the subsequent chapters in this section (chapter 9, 10 and 11), to help illustrate the general themes that were found to be common to several learners.

§8.1: An overview of Tajinder's case in terms of alternative explanatory principles.

From the wealth of detail available the following points give an overview of the case:

- at the start of the course Tajinder recognised three categories of chemical bonding (covalent, ionic and metallic).
- later in the course Tajinder was able to accept polar bonding as "in between" ionic and covalent - and then later still to explain this in terms of other concepts (electron density, electronegativity).
- during the course Tajinder came to accept other phenomena could be included under the general concept of chemical bond, i.e. hydrogen bonding, dative bonding, van der Waals' forces.
- Tajinder's definitions of chemical concepts became more sophisticated, for example the covalent bond was simply 'sharing' of electrons at the beginning of the course, but later became understood in terms of forces between the bonding electrons and the nuclei, and in terms of the overlap of atomic orbitals to form molecular orbitals.
- Tajinder acquired new concepts which related to bonding, such as electronegativity, orbitals, electron density, core charge, electron spin and energy levels.

During the period investigated Tajinder increased the number of 'tools' in his chemist's conceptual toolbox, the range of application of those tools, and his competence in using them.

The brief outline above gives little indication of the extent to which bonding-related concepts became integrated in Tajinder's cognitive structure during his course. In the previous chapter it was suggested that many of Annie's comments in her interviews could be organised into two complexes of related ideas, each one based in a core *explanatory principle* that formed the starting point for much of her thinking. It will be argued here that Tajinder's utterances about chemical bonding can largely be understood as related to one of three such *explanatory principles*. I have labelled these three principles as the OCTET RULE EXPLANATORY PRINCIPLE, the COULOMBIC FORCES EXPLANATORY PRINCIPLE, and the MINIMUM ENERGY EXPLANATORY PRINCIPLE. These explanatory principles may be paraphrased as:

the OCTET RULE EXPLANATORY PRINCIPLE

i) atoms are stable if they have full outer shells, and unstable otherwise;
ii) an atom that is unstable will want to become stable;
iii) the unstable atom will form bonds such that it seems to have a full outer shell, and thinks it has the right number of electrons.

the COULOMBIC FORCES EXPLANATORY PRINCIPLE

i) there is always a force between two charged particles;
ii) similar charges repel, opposite charges attract;
iii) the magnitude of the force diminishes with increasing charge separation;
iv) forces acting on particles may be balanced at equilibrium.

the MINIMUM ENERGY EXPLANATORY PRINCIPLE

i) configurations of physical systems can be ascribed an energy level;
ii) lower energy is more stable than higher energy;
iii) physical systems will evolve towards lower energy configurations.

In the following pages the findings from the case study are presented, and discussed.

§8.2: Tajinder's knowledge of bonding at the start of the course.

Tajinder was aware of three types of bonding at the start of his A level course. He included three categories of bonding in a concept map drawn during an introductory class (September, 1992). He later suggested the same categories when asked to name and draw the types of bonding he was familiar with (November, 1992).

He described these classes of bonding in the following terms:

- Transfer of electrons takes place in ionic bonding.
- In covalent bonding, electrons are shared.
- Metallic bonding takes place in metals. In this type of bondings [sic] the electrons are free to move around the area of the metal.

§8.2.1: An explanatory principle based on the octet rule.

At the start of his A level course, then, Tajinder had already acquired a limited range of concepts related to chemical bonding. When first interviewed (interview T1, October, 1992) it became clear that to the extent that these concepts were connected in cognitive structure they were linked through an explanatory principle based on *the octet rule*.

The octet rule is a 'rule of thumb' that is fairly successful in elementary chemistry as few exceptions are met during most introductory courses. However, the rule does not have any genuine explanatory power, being merely a heuristic for discriminating stable and unstable structures at the atomic level. Despite its heuristic value, the octet rule does not suggest any ***mechanism*** by which noble gas electronic configurations arise, merely that such configurations tend to be stable.

During his first research interview Tajinder demonstrated that for him the octet rule had provided the basis for an explanatory principle. The explanatory principle that Tajinder used could be summarised:

i) atoms are stable if they have full outer shells, and unstable otherwise;
ii) an atom that is unstable will want to become stable;
iii) the unstable atom will form bonds such that it seems to have a full outer shell, and thinks it has the right number of electrons.

It will be noted that in the absence of any physical mechanism for bond formation, an anthropomorphic explanation is used - atoms are imbued with, or at least spoken of as if imbued with, consciousness and the ability to act on their thoughts. (This is a feature that was found to be common with other chemistry learners, as is demonstrated in chapter 11, §11.3).

§8.2.2: Tajinder's application of the octet rule explanatory principle.

The first interview showed how Tajinder used his OCTET RULE EXPLANATORY PRINCIPLE to find a common basis to the three types of chemical bond he was familiar with.

So for Tajinder these classes of bond were explained as follows:

- **Covalent bonding**: In covalent bonding electrons are shared because of the number of electrons needed for an atom to be stable. For example, in hydrogen both atoms ***think*** [sic] they have two electrons. Although the electrons are shared each is perceived as ***belonging to*** the atom from which it originated, and if the bond is broken each atom will get its own electron back. (*Ownership* of electrons {§11.1.4}, and the tendency to see the ***history*** of an electron as significant {§11.4} were found to be common features of colearner thinking).

- **Ionic bonding**: This is where an atom loses its outermost electron to another atom which needs one electron in its outer shell to become stable. The sodium atom, for instance, is not stable and *needs* to lose an electron to have a full outer shell, so it loses it to a chlorine atom.
- **Metallic bonding**: An isolated sodium atom would become stable if it could lose an electron. In the context of metals electrons can leave atoms. Metallic bonding involves lots of free electrons which originate from the outer shells.

In each case the bond allows the atoms to have the stable electronic configuration.

§8.2.3: Limits to the range of convenience of the octet rule explanatory principle.

Although the OCTET RULE EXPLANATORY PRINCIPLE provided Tajinder with a basis for conceptualising his three categories of bonding according to a common principle, it also led to deductions that were inconsistent with aspects of CURRICULUM SCIENCE, and which would potentially impede his progress in A level chemistry. That is, it acted as a SUBSTANTIAL LEARNING IMPEDIMENT (§1.5.3).

Ionic bonds are distinguished from just forces: Although ionic bonding was defined in terms of the OCTET RULE EXPLANATORY PRINCIPLE, Tajinder was not able to explain the integrity of the ionic lattice from this perspective. So in his scheme the ionic bond was the transfer of electrons between particular ion pairs, whereas the structure held together because of the positive and negatives. Tajinder supposed that ions were *equally attracted* to their neighbours, but *not equally bonded*. Each sodium ion could only be bonded to one chlorine ion; then no more bonds could be formed, as there were no more outer electrons available. (Tajinder's thinking about ionic bonding at this stage of the course included features that were also found in the data from other learners: construing the ionic bond as electron transfer (§11.2.2), limiting the number of ionic bonds according to valency (§11.5), and discriminating between two classes of interaction - bonds and just forces - between neighbouring counter ions in the ionic lattice (§11.7.1). These features are all considered in chapter 11.)

Covalent bonds are not conceptualised in terms of forces: Although a hydrogen molecule contains charged particles, this is not considered the be like the ionic case - Tajinder's perception is that the charges just stop the molecule falling apart (whereas the bond is the sharing of electrons to give full outer shells).

Intermolecular attractions are not bonds: Tajinder thought there could be 'positive-negative attractions' between molecules, although not if they were neutral.

He thought that perhaps there could be a force - but not a bond. (This was another feature which was also found with other learners, and is discussed in chapter 11, §11.7).

It is seen that Tajinder did have some ideas about the roles of charges and forces in (what we would call) chemical bonding. However, as Tajinder defines bonds in terms of his OCTET RULE EXPLANATORY PRINCIPLE, he did not include these force ideas within the realm of his bonding concept.

§8.2.4: Tajinder's thinking about forces at the start of his course.

It was noted above that Tajinder did not consider chemical bonding was concerned with forces. When Tajinder was asked about physical situations where forces were acting (interview T2, February 1993) it was found that his ideas were not always consistent with the CURRICULUM SCIENCE interpretation.

Newton's laws of motion. Whereas Newton-2 (§3.1.3) would associate balanced forces with zero acceleration, Tajinder associated this with zero speed. Tajinder also demonstrated alternative conceptions about the forces involved in interactions between several bodies. From Newton-3 it is known that when two bodies interact they are subjected to forces of equal magnitude, but opposite direction (c.f. 3.1.3). However, when Tajinder was asked about the case of an object placed on the earth, he did not think the forces could be of the same magnitude.

Tajinder also had non-Newtonian alternative conceptions about the gravitational forces acting in a solar system. He believed that the earth attracted the moon (as it does) but explained they did not get any closer as the moon *repelled* the earth. Nor did his model follow an inverse-square law: a planet furthest from the sun would be attracted the *most*, while the planet nearest would be *repel* the sun the most.

Interactions between charges. Tajinder did suggest that a larger charge or smaller separation should lead to a larger force, but he also thought that if two charges interacted the smaller charge would experience the greater force, and implied that the mass of the charges affects the force (perhaps not clearly distinguishing the force with its effect). Notwithstanding these ideas about charges in abstract, Tajinder did not always follow these rules in applying the ideas to atomic situations: for example he thought all electrons in a silicon atom would be *equally attracted* to the nucleus (interview T2, February 1993). In the first interview (October 1992) he had referred to a positive-negative bond that attracts the electrons to the nucleus, as there was always attraction between positive and negative. However he was not sure if *the nucleus* was attracted *to* the electrons.

Equilibrium. Ultimately Tajinder would come to understand that chemical processes (*e.g.* bond formation) could be understood as the results of systems with unbalanced forces. The system would evolve to a new configuration where an equilibrium of forces was established. However initially Tajinder had difficulty with the concept of equilibrium. For example at one point in the first interview (October 1992) he suggested that the repulsions present in a hydrogen molecule were greater than the attractions. He also thought that two protons in a nucleus would experience repulsion, but not attraction - although they were held together by a force (T2, February 1993). At a later date Tajinder discusses van der Waals' forces between two neon atoms and suggested that the attraction of the nucleus for the electrons (of the adjacent atom) is greater than the repulsion between the electrons (T3, April 1993).

The CONSERVATION OF FORCE EXPLANATORY PRINCIPLE It was clear from the early interviews that Tajinder did not seem to clearly distinguish the concept of force, from that of charge, or from that of energy. For example when Tajinder discussed the interaction between the nucleus and electrons in a sodium atom, he appeared to conceive this as one central attraction from the nucleus to all the electrons (T1, October 1992). When Tajinder wrote in an assessment (about ionisation energy) that when one electron is removed from a shell the shell is subsequently held more tightly (March 1993) he *could* have been thinking about the effect of reduced repulsion between electrons. However over time it became clear that Tajinder applied an explanatory principle that I have labelled CONSERVATION OF FORCE. For example in a discussion about ionisation energies Tajinder refers to "how much force the atom has" (T5.A064).

§8.2.5: Tajinder's application of his conservation of force explanatory principle.

Tajinder's CONSERVATION OF FORCE EXPLANATORY PRINCIPLE could be summarised:

- an atomic nucleus has a certain amount of force available,
  that depends upon the charge on the nucleus,
  and is shared between the electrons.

When comparing the ionisation energies of beryllium and magnesium Tajinder referred to various relevant factors, but then suggests that magnesium does not have as much attraction to the outermost electrons as there are more electrons to attract (T5, April 1993). On another occasion he refers to the attraction in a helium atom being spread out over two electrons (T6, May 1993). In a subsequent interview Tajinder gives a clearer exposition of this conception (T7, May 1993), when he compares the helium atom to the helium ion. His argument followed the lines:

> In the *ion* the protons only have one electron to attract.
> Slightly less energy is needed to remove the *atom*'s electron, because there are two electrons for the nucleus to attract.
> The amount of force the nucleus can give out is spread over the number of electrons there are -
> as if you've got an extra electron, the nucleus can not just give out extra force.

Tajinder's notion of *conservation of force* led to appropriate predictions in some contexts. Successive ionisation energies within an electron shell do increase as the repulsion between electrons is reduced, and the radius of the species decreases. Tajinder explained the same phenomenon from the idea of *conservation of force*, that there were less electrons to share the nucleus' attraction, so each electron received a larger share of the force.

It would have been interesting to have allowed Tajinder to follow through this logic as far into the course as possible, and see whether he spontaneously found the need to supplant this conception. However this would have been unethical (§4.3.2), so Tajinder was presented with the orthodox scientific views. Later in the same interview Tajinder referred to the electron in the Li^{2+} ion being subject to more attraction than an electron in the Li^{+} ion. Again his initial reasoning was that the effect of the nuclear charge was spread among the two electrons in the 1+ ion. When challenged he was able to form a new argument based on electron repulsion. In the end of year examination Tajinder wrote that "the Mg^{+} ion has a stronger pull on the second electron as the first has been removed" (June, 1993) - a comment that seems to be sensible from the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE

In his second year of the course Tajinder explained that a carbon atom would pull the bonding electrons in two carbon-hydrogen bonds less well than one, because its ability to pull electrons is being stretched (T13, November 1993). Again, rather than consider the additional repulsions, Tajinder seems to consider that the *amount of pull* available is limited.

§8.3: Tajinder's adoption of new explanatory principles.

During his course Tajinder supplemented his existing explanatory principles (the octet rule and conservation of force) with two additional principles more closely based on the curriculum science he was being taught.

§8.3.1: Acquiring an explanatory principle based on Coulombic electrostatics.

At the start of his A level course Tajinder already thought that there was always attraction between positive and negative charges (T1, October 1992) - although in practice he did not always apply this principle.

Much of the classroom presentation of chemical ideas that Tajinder experienced was based around basic electrostatics, i.e. Coulomb's law. In qualitative terms these ideas may be expressed:

i) there is always a force between two charged particles;
ii) similar charges repel, opposite charges attract;
iii) the magnitude of the force diminishes with increasing charge separation;
iv) forces acting on particles may be balanced at equilibrium.

Tajinder's construction of a conceptual framework for understanding chemical bonding based on the electrostatic explanatory principle was hindered by his preexisting ideas which acted as SUBSTANTIAL LEARNING BLOCKS (§1.5.3):

1: his own alternative conceptions of electrostatics, which meant that his interpretations of the interactions present between charges did not always match the orthodox CURRICULUM SCIENCE view;
2: Tajinder's use of the OCTET RULE EXPLANATORY PRINCIPLE, which already 'explained' chemical bonding for him. (The limitations of this principle, discussed above, which are apparent from the viewpoint of CURRICULUM SCIENCE, would not be readily detected by someone defining and demarcating bonding phenomena from *the perspective of* the OCTET RULE EXPLANATORY PRINCIPLE, c.f. §2.2.3).

For example when discussing metallic bonding quite early in his course, Tajinder stated that there was a force between the atoms joining them together (T2, February 1993). He described this as *positive and negative forces*. These were not the same thing - similar *forces* attract, whilst opposite *forces* repel. At this point Tajinder had not clearly distinguished charges from forces. Similarly in a concept map written as part of his revision for first year examinations Tajinder referred to the forces holding ions together as being "electrostatic forces, +ve and -ve" (June 1993).

As he proceeded in his studies Tajinder was able to explain the van der Waals' interactions between two adjacent atoms in terms of forces, but thought that the attractions would be larger than the repulsions (T3, April 1993). Shortly after this (T4, April 1993), Tajinder talked of the nucleus of one atom attracting the electrons of another - but suggested that there was a sort of force that holds the atoms together *as well* (T3, April 1993).

By the end of the first year Tajinder acquired a concept of hydrogen bonds in terms of attractions between ∂+ and ∂- ends of molecules. However, at one point during his second year he commented that he was not sure if Coulomb's law could be applied to hydrogen bonds, as Coulomb's law was really about electrons (T11, October 1993).

§8.3.2: Tajinder's developing application of the coulombic forces explanatory principle.

By the end of the first year of his course Tajinder was beginning to develop a conceptual framework for understanding bonding based on the COULOMBIC FORCES EXPLANATORY PRINCIPLE. He explains metallic bonding in terms of the attraction between electrons and the positive ions, and refers to there being only electrostatic bonds present (T8, June 1993). He comments that all the bonds are equal in an ionic structure such as sodium chloride, and refers to forces due to oppositely charged ions. However these comments are mixed with others that are based on the OCTET RULE EXPLANATORY PRINCIPLE. At this time covalent bonding is still understood in terms of sharing electrons to obtain stable electronic configurations.

Tajinder is able to apply electrostatic ideas in a number of contexts: for example that anions are larger than the parent atom as the gained electrons lead to additional repulsion between electrons (T4, April 1993). He appreciates how ionisation energy depends on core charge, and the nucleus-to-electron distance (T5, April 1993; T6, May 1993; T7, May 1993) and how the shapes of molecules could also be explained in terms of electrostatic repulsions (T9, June 1993; T23, May 1994).

Over his course Tajinder comes to apply electrostatic principles to the three categories of bonding he had at the start, and incorporate them in a complex of conceptions derived from the COULOMBIC FORCES EXPLANATORY PRINCIPLE. He is able to explain covalent bonding in terms of the nucleus of one atom having ***a certain amount of attraction*** (c.f. §8.2.5) for another atom's electrons, and this force being what holds the molecule together (concept map on chemical bonding prepared as revision exercise, June 1993). He explains the process of bond formation as the core charges attracting electrons from the other atom into 'gaps' in their electronic configuration, so the atoms are attracted together to form a bond (T16, January 1994). Near the end of the course the bond in the hydrogen molecule is explained in terms the attraction of each nuclei for both electrons, balancing the repulsions present (T20, April 1994).

Tajinder came to understand the metallic bond as being formed when there is an attraction, a force, between one of the nuclei and the electrons on another atom: again an equilibrium is reached (T21, April 1994).

Similarly, Tajinder is able to explain how in ionic bonding, there is an attraction between the ions - because one has a positive charge and one a negative charge - but they do not coalesce because there will be repulsions between nuclei, and between electrons, and the repulsions equal the attractions (T20, April 1994). At this point Tajinder considers that ionic bonding is an attraction between positive and negative ions, rather than a transfer of electrons (T23, May 1994).

§8.3.3: Tajinder's application of the minimum energy explanatory principle.

Tajinder acquired the idea of the lowest available energy level as an explanatory principle early in his course. This principle could be stated:

i) configurations of physical systems can be ascribed energy levels;
ii) lower energy is more stable than higher energy;
iii) physical systems will evolve towards lower energy configurations.

Although a physical system evolving to minimum energy may be considered equivalent to the effect of forces acting on the system until an equilibrium is reached, Tajinder did not continue the study of physics past G.C.S.E. level, and he did not tend to perceive the notions of minimising energy, and the effect of electrostatic forces as directly related.

When Tajinder was interviewed at the start of the third term, having been introduced to the idea of seeing chemical processes in terms of energy levels in class, he explained that if you had two atoms, and they joined together, the energy would be low (T3, April 1993).

When considering the electronic configuration of beryllium Tajinder explained that this would be $2s^2$ rather than s^1p^1 as the latter would be a higher energy (T3, April 1993). However Tajinder also suggested that a p_x orbital must be at a lower energy level than the p_y orbital as the former was always filled first. Here Tajinder did not appreciate the arbitrary nature of labelling the degenerate orbitals.

As with the OCTET RULE EXPLANATORY PRINCIPLE, Tajinder seemed to need to imbue the atoms concerned with human thoughts and desires - *at least* metaphorically - as a mechanism for achieving stability. For example in his last term of the course Tajinder explained that it required energy to promote an electron in a molecule, as when a molecule forms it *wants* to stay at the lowest energy (T21, April 1994).

Tajinder's adoption of the MINIMUM ENERGY EXPLANATORY PRINCIPLE was largely tied to the development of the concept of molecular orbital. The principle was applied to the covalent bond, where two hydrogen atoms form a bond, forming two molecular orbitals (bonding and antibonding); and in a metal where there are molecular orbitals formed from overlap of atomic orbitals - Tajinder suggested these molecular orbitals must be at lower energy otherwise the metal would not exist (T21, April 1994). Tajinder did not at first think this idea could be applied to an ionic material such as NaCl - but then decided that there *were* molecular orbitals, but they were so polarised that they did not show, as the [*i.e.* bonding] molecular orbital was all around the chlorine ion. This may be considered as a sophisticated observation. This *explanatory principle* was applied to polar bonds, such as in lithium iodide, tetrachloromethane, water and hydrogen fluoride. Tajinder thought there might be a scale, so the more covalent the species, the more dominant the molecular orbital, and the more ionic, the less dominant. (In CURRICULUM SCIENCE terms in the more ionic case the molecular orbital would be more similar to the atomic orbital). However Tajinder did not consider hydrogen bonding could fall within a molecular orbital explanation, as that was just an attraction (c.f. §11.7).

§8.4: Tajinder's progression in understanding chemical bonding.

By comparing Tajinder's understanding of chemical bonding at the end of his course, with his understanding when he started his A level studies (i.e. as described in §8.2) it is clear that his understanding has shown considerable progression - a good deal of learning has taken place. This may be demonstrated by considering the range of relevant tools he has acquired for his chemist's tool box (§1.7.2), and the increased range of application of his concept of 'chemical bonding'.

§8.4.1: Tajinder's acquisition of new conceptual tools related to 'bonding'.

During his course Tajinder acquired new conceptual tools for thinking about chemical bonding and related themes.

Electronegativity: by the second term Tajinder had acquired a concept of *electronegativity*, as a tool for deciding the type of bonding - a high difference in electronegativity suggests ionic bonding, but a low difference suggests covalent (T2, February 1993). However this rule would suggest calcium chloride, which Tajinder thought was covalent, was ionic.

Orbitals: Tajinder had acquired the use of the term *orbital* within the first month of his course (the concept was used in his organic chemistry classes). However initially Tajinder thought that orbitals were spheres with electrons at opposite sides (T1, October 1992). The term was not clearly distinguished from his existing concept of shell, and he tended to use the two terms as if synonymous (c.f. §9.2.1). In a subsequent research session, where Tajinder undertook Kelly's repertory test, he used the construct "shows rough placement of electrons in orbitals" to describe figures that actually represented electrons in *shells* (November 1992).

However during his second term Tajinder was able to describe an orbital as an area [sic - i.e. volume] around the nucleus of an atom, where an electron is likely to appear, that is, where 95% of the time you could find the electrons (T2, February 1993). Tajinder was apparently confusing the orbital itself with the arbitrary boundary drawn in diagrams, an error which recurred (T5, April 1993; T6, May 1993, c.f. §9.2.4). He knew there were four types of orbital: s, p, d and f. He was not clear how *orbitals* related to *shells*, but could say that if all the p-orbitals were full of electrons then this would show like a sphere shape of electrons smeared out, and he thought this [i.e. the sub-shell] was what was represented by the circles drawn in elementary work. He continued to confuse orbitals, shells and sub-shells for some time (T6, May 1993; T14, November 1993).

At this stage Tajinder did not appreciate that the atomic orbitals interact to form molecular orbitals in bonding. He classified figures representing molecular orbitals as 'show[ing] s and p orbitals' (Kelly's construct repertory test, November 1992), and thought it was possible to draw molecules of oxygen and methane showing the s and p orbitals (T2, February 1993, c.f. §9.3.2).

In his third term Tajinder described an orbital as just the probability of finding the electron in a certain area [*sic*], and was aware that two electrons could go in the same orbital, but he would confuse orbital lobes with the orbitals themselves (T3, April 1993). Tajinder was not sure if covalent bonds could be counted as orbitals (T4, April 1993). He thought that electrons were restricted in where they can be in space, because they are in orbitals (T5, April 1993).

Electron density: Tajinder seemed to accept a notion of electron density readily, and was able to discuss the overall electron density of electron configurations (T3, April 1993). He could apply this idea to atoms such as neon - where the p electrons form a sphere when smeared out - and fluorine - which has not got a spherical electron density overall, because it is missing an electron and the others cannot move over to make up for this (T5, April 1993).

Core charge: By the third term Tajinder was able to use the concept of core charge - being the charge in the nucleus minus shielding electrons - and could generally work out core charges (T3, April 1993). Sometimes when using the concept of core charge in an explanation he would forget that this means he has already allowed for the effect of core electrons, and would introduce the effect of these electrons into his argument (T4, April 1993; T6, May 1993). He was sometimes uncertain when he should use his new tool of core charge, and when to use the more familiar idea of nuclear charge (T5, April 1993).

Electron spin: When Tajinder first used the term spin-pairing he did not seem to have any notion of what is implied, beyond there being two electrons in one orbital (T3, April 1993, c.f. §9.2.6). He seemed unclear whether spin is a property of electrons or of orbitals (T5, April 1993). At this time he commented that electron spin does not really mean anything, because the electron does not spin as it is part wave. Rather, he thought that electrons are *said* to spin in opposite directions to explain how two electrons can be in the same orbital without a very large repulsion. (This comment, perhaps a slightly distorted version of a comment presented to the group during class, seems to suggest that Tajinder was quite open to science being incomplete, and a human construction).

Energy levels: Tajinder acquired the use of the concept of energy levels during the first year of the course, although he initially referred to them as shells or orbitals (T5, April 1993, c.f. 9.2.3).

§8.4.2: Tajinder develops new categories of chemical bond.

At the beginning of the course Tajinder only had three categories of chemical bond: covalent, metallic and ionic. He accepted that there might be *forces* between adjacent molecules, but a this was not considered to be *chemical bonding* - which was understood in terms of the OCTET RULE EXPLANATORY PRINCIPLE. The construction of a complex of ideas derived from the alternative COULOMBIC FORCES EXPLANATORY PRINCIPLE allowed Tajinder to include new forms of interaction as chemical bonds:

Van der Waals' forces. Tajinder came to understand van der Waals' forces in terms of electrostatic attractions, forces from one nucleus to the electrons of another atom (T3, April 1993). He understood that this was possible even when atoms were neutral and symmetrical, as the sphere described an overall picture over time, and (at any one instant) there were 'electron lumps'. Tajinder explained that as the electrons move around there would always be the possibility of little gaps (T11, October 1993). He thought that the electrons could be all down one side of the molecule for an instant (T9, June 1993).

Hydrogen bonding. At the beginning of his course Tajinder did not have a concept of hydrogen bonding, but by the end of the first year he was able to describe this as a certain type of attraction between ∂+ and ∂-, and so a type of bond (T8, June 1993). Tajinder included this as a category of bonding (which took place between hydrogen and a non-metal) on a concept map produced at this time (concept map on chemical bonding, prepared as a revision exercise, June 1993).

Polar bonding. At the start of the course Tajinder would class bonding in compounds as ionic or covalent (c.f. §11.6.2). The carbon-chlorine bond was considered to be in the same class as the hydrogen-hydrogen bond, *i.e.* covalent (T1, October 1992). Tajinder used water as an exemplar for covalent bonding when he was asked to draw the types of bonding with which he was familiar (November, 1992). By the second term Tajinder was talking of differences in electronegativity being used to determine bond type, but in terms of a dichotomy: a low difference meant covalent, a large difference polar (T2, February 1993).

When interviewed at the end of the first year and asked to list the types of bond he knew about Tajinder did not include polar (T8, June 1993). However later in the same session he did refer to electrons in the carbon-hydrogen bond being pulled more toward the carbon, and Tajinder referred to the bond in methane as covalent *and* polar. He then reported that bonding in compounds was normally polar, which was something in between ionic and covalent. This view (that polar bonds were the most common, and were to be understood as something in between ionic and covalent) was reiterated in a concept map Tajinder drew about this time (concept map on chemical bonding, prepared as a revision exercise, June 1993). At this point Tajinder's concept of the polar bond did not seem to be built on sound electrostatic principles: the comment that *the polar bond involved a type of attraction between the* ∂+ *and* ∂- *ends of a bond* suggested some confusion between cause and effect (T8, June 1993).

Often when Tajinder referred to polar bonding he would simply explain this in terms of electronegativity difference causing the electrons to be nearer one end of the bond (T9, June 1993). However sometimes Tajinder would take the explanation further, explaining for example that an iodine atom would attract electrons more than a lithium atom (T9, June 1993), and that bonding electrons are attracted more to oxygen than hydrogen in water, as oxygen has a larger pull on them (T11, October 1993). In discussing the carbon-chlorine bond Tajinder took the argument one further step towards basic principles - chlorine pulls the electrons more because it has a core charge of +7, so the electron density is pulled in until the electrons reach a point where they cannot go any further because of the repulsions from the chlorine [non-bonded] electrons, and the attraction of the carbon nucleus (T17, February 1994).

Dative bonds. Near the end of his first year Tajinder described a diagram of an aluminium chloride dimer as "completely wrong" as it showed chlorine with two bonds (T9, June 1993). Rather he thought (in accordance with OCTET RULE EXPLANATORY PRINCIPLE) that a chlorine atom already had seven electrons in its outer shell, so it only needed one more, so it would only form one bond. However he was then able to discuss how there would be an attraction between molecules, although this would be electrostatic *attraction*, and *not bonds*. He suggested that there was a gap in the electron density cloud around aluminium, and as chlorine had full density the [aluminium] nucleus pulls electrons from the chlorine. This effect, he thought, was *like* a force (c.f. §11.7.4).

§8.4.3: Tajinder's developing understanding of chemical bonding is related to his acquisition of new explanatory principles.

At the start of his A level chemistry course then, Tajinder's thinking about chemical bonding was largely derived from his OCTET RULE EXPLANATORY PRINCIPLE. This explanatory principle was of limited utility in understanding chemical bonding to the depth required at A level.

By the end of his course he had acquired two other explanatory principles which could be used to explain chemical bonds: the COULOMBIC FORCES EXPLANATORY PRINCIPLE, and the MINIMUM ENERGY EXPLANATORY PRINCIPLE.

Tajinder used his COULOMBIC FORCES EXPLANATORY PRINCIPLE to derive a complex of ideas to enable him to explain bond formation in terms of the nuclei of one atom attracting electrons of another, so that the atoms come together. Ionic, covalent, metallic, polar, hydrogen, dative bonds and van der Waals forces could be explained as due to electrostatic forces between the component species. A bond was seen as an attraction between two species (T12, October 1993), as something that keeps atoms held together, a force (T14, November 1993). Solvation was understood as the formation of bonds (T19, April 1994), *albeit* not fixed bonds, but ones constantly breaking and forming (T22, May 1994).

Tajinder's MINIMUM ENERGY EXPLANATORY PRINCIPLE was closely associated with the formation of molecular orbitals. This explanatory principle did not become as well integrated into existing cognitive structure during the course as the COULOMBIC FORCES EXPLANATORY PRINCIPLE. For example (for Tajinder) hydrogen bonds did not fall within its range of convenience (T21.D224).

The importance of Tajinder's new explanatory principles in his developing understanding of chemical bonding is considered in more depth in appendix 28.

§8.4.4: Stability of the octet rule explanatory principle.

So even when Tajinder had begun to construct a new explanatory conceptual scheme for understanding chemical bonding based around the COULOMBIC FORCES EXPLANATORY PRINCIPLE, he still tended to apply his OCTET RULE EXPLANATORY PRINCIPLE in some contexts. At the start of his third term he states that all elements *try* to gain noble gas configurations to become stable (T4, April 1993). At the end of the first year of A level work he talks about the covalent bond between two hydrogen atoms in terms of the two atoms being held together because they do not *want* to be unstable, so they *share* electrons to *think* they have noble gas configurations (T8, June 1993). He defines covalent bonding as "sharing of electrons", "the amount of electrons being shared depends upon the amount of electrons needed to become a noble gas configuration" (concept map on chemical bonding prepared as a revision exercise, June 1993).

When, during the third term, Tajinder undertook Kelly's construct repertory test, a number of constructs related to the OCTET RULE EXPLANATORY PRINCIPLE were amongst those elicited (May 1993). These constructs were:

- need an extra electron to have full outer shell
- not have noble gas configuration
- shows noble gas configuration
- does not have full outer shell

Even in the second year of his A level course Tajinder would use the OCTET RULE EXPLANATORY PRINCIPLE when discussing bonding. For example he talked of a sodium atom which would lose an electron to form an ionic bond - it *wanted* to become stable, an octet, a full outer shell (T17, February 1994, see appendix 29, §A29.2). On other occasions Tajinder talked of oxygen atoms that *want* an octet state to become stable; and that share electrons because they *want* to gain two electrons to have a full outer shell (T16, January 1994, see appendix 29, §A29.1); of hydrogen and chlorine atoms that *want*ed to gain a noble gas configuration (T11, October 1993, see appendix 28, §A28.2.1); and of carbon *want*ing to gain a full outer shell, and sharing electrons so it ***thinks*** it has eight (T10, October 1993). According to Tajinder a group 1 element *wants* to lose an electron to become stable, and iodine *wants* to gain an electron (T12, October 1993).

Tajinder thought stability was to do with the arrangement of electrons around the nucleus, and was inversely related to reactivity. So francium and cæsium were not stable as they *want* to react, whereas fluorine was reactive - it *need*ed an extra electron to gain a full shell (T10, October 1993). When it was pointed out to Tajinder that fluorine *gas* was not stable (*i.e.* was reactive) despite a full outer shell, he accepted that the outer shell criterion was not a good guide to stability. Despite this acknowledgement, later in the interview, Tajinder explained the formation of a dative bond between two aluminium chloride molecules in terms of the aluminium ***thinking*** it was stable, as it ***thought*** it had eight outer electrons.

The ***polar*** bond is particularly important when considering the development of Tajinder's understanding of chemical bonding. Tajinder did not initially have such a category. Then it was considered simply as being ***in between*** ionic and covalent. Later it was understood in terms of the attraction of the two core charges for the bonding electrons. However even after Tajinder had discussed the bond in these terms, he would later talk of the unequal *share* of electrons in a carbon-chlorine bond being due to chlorine's greater *desire* for electrons. He also said that chlorine had more pull on the electrons in a hydrogen-chlorine bond, whereas hydrogen did not really *mind* (T18, March 1994, see appendix 29, §A29.3).

§8.4.5: Tajinder's pluralist approach to explaining chemical bonding.

During his course Tajinder constructed new ways of explaining chemical bonding, without completely putting aside his preexisting explanatory principle. The evidence from this case study demonstrates that Tajinder's progression did not involve a sudden switch between explanatory principles, but a gradual tendency to use his OCTET RULE EXPLANATORY PRINCIPLE less as he developed explanations based on the alternative foundations of Coulombic forces, and minimising energy.

For example at the end of his first year of A level study Tajinder explained his ideas about ionic bonds (T8, June 1993, see appendix 28, §A28.1.1). He referred to the forces due to the oppositely charged ions, and thought that all bonds in sodium chloride were equal, whereas he had previously suggested ions were *equally attracted* to their neighbours, but *not equally bonded* (T1, October 1992). However he started his explanation of ionic bonding in terms of the *needs* of atoms to gain or lose electrons to reach noble gas configurations. He still thought that as sodium can only lose one electron, it could only form one bond. Thus Tajinder had come to a paradox - a sodium atom can only form one bond, but actually has six equal bonds. He attempted to reconcile this contradiction with the suggestion that there was one bond, but it moved around. Tajinder suggested that the donated electron moved around, but he also thought the electron cannot leave the anion - another paradox.

Tajinder was asked to consider precipitation (double decomposition) processes. It was thought that this would be a context where the inadequacy of the *electron transfer* definition of ionic bonds would be clear. For example if a solution of barium nitrate was mixed with a solution of sodium sulphate, a precipitate of barium sulphate would be formed. (This example was chosen because Tajinder thought barium sulphate would be ionic, whereas he was unsure of the bonding in silver nitrate which had been the first example mooted). It might be considered that the ionic bonds in the barium sulphate 'obviously' could not be understood in terms of electron transfer from barium to sulphate, as these species already existed as ions before mixing. However Tajinder saw things differently. As - from his OCTET RULE EXPLANATORY PRINCIPLE - the formation of ionic barium sulphate had to involve electron transfer from barium to sulphate, the reacting species were assumed to be solvated barium atoms and neutral sulphate 'molecules'. It was only when this view was probed that Tajinder accepted that the reactant solutions would ***not have had time*** to return the electrons on mixing. Tajinder's scheme involved:

barium nitrate solution - contains ions due to electron transfer from barium to nitrate
and
sodium sulphate solution - contains ions due to electron transfer from sodium to sulphate
which on mixing gives
a solution containing neutral barium and neutral sulphate
which react to form a precipitate of barium sulphate
which is ionic due to electron transfer from barium to sulphate
leaving sodium nitrate ion-pairs in solution

According to Tajinder, this reaction occurred because barium had *want*ed to lose two electrons to get a noble gas configuration, and had given them to the sulphate. He did not explain *why* the barium had reclaimed electrons from the nitrate anions. (This is discussed further in appendix 28, §A28.1.2).

Another example is from early in Tajinder's third term when he was interviewed about the electronic configurations of atoms. He thought that the inert gases have stable electronic configurations because of the electrons in the orbitals; that is, the atoms *want* to fill up electrons on each orbital to be stable (T3, April 1993). The second electron in a shell went into an s-orbital, not a p-orbital because it *wants* to become like a noble gas configuration, to become stable. It did not *want* to have the electron in the p-orbital. However Tajinder also gave the alternative explanation that the s^1p^1 configuration's energy level would be higher. Tajinder also referred to spin-pairing in this context, although he did not seem to be clear how this idea was relevant. Here stability was associated with low energy, *and* noble gas configurations, and both principles were seen anthropomorphically.

In his end-of-year examination Tajinder explained why he thought neon had the highest molar first ionisation energy of the elements in period 2 (June 1993). His explanation contained ideas derived from both the COULOMBIC FORCES EXPLANATORY PRINCIPLE and the OCTET RULE EXPLANATORY PRINCIPLE: neon has the highest core charge, has a full outer shell, and has no *desire* to have its electrons removed, as it already has noble gas configuration. His discussion of metallic bonding in the same examination included ideas of sodium and magnesium atoms *having to lose* one and two electrons (respectively), and also the electrostatic forces being stronger in the case of magnesium.

During an interview in the second year Tajinder was asked why hydrogen and chlorine react (T11, October 1993, see appendix 28, §A28.2.1). He suggested that more energy is given out during the reaction than taken in. However later in the interview he suggested the atoms *want* to obtain a noble gas configuration, or stable outer shells. When his attention was drawn to diagrams of the hydrogen and chlorine molecules in the reactants (with the atoms already having noble gas electronic configurations) Tajinder used an anthropomorphic version of the electronegativity concept: that chlorine *wanted* more of the electrons to itself, where hydrogen - being electropositive - *wanted* to get rid of electrons.

Tajinder's tendency to operate with a mixture of ideas based on different - and apparently incongruent - explanatory principles, is discussed in more detail in appendix 29. For example, in a single interview, (T16), Tajinder was able to 'explain' the bond in molecular oxygen in terms of atoms *wanting* octets, lowering the energy state of the system, and in terms of the electrostatic charges between nuclei and electrons (§A29.1). Tajinder tended to draw freely upon ideas from his three different explanatory schemes in various contexts, such as the reason for a bond forming between hydrogen atoms, the polarity of carbon-chlorine bonds, bonding in metals, the reaction between sodium and chlorine (§A29.2); organic reaction mechanisms (§A29.3); and the types of bond in ice (§A29.4).

Chapter 9.

Learners' difficulties in understanding electron orbitals.

> I: Can you have an orbital with no electrons in it?
> T: If you had that, then it wouldn't be an orbital.
> T3.A336

§9.0: The orbital concept.

As described in chapter 6 (§6.1.2), the learners in this study were following an examination syllabus which required them to learn about quantum numbers, atomic orbitals, energy levels, pairing of electrons, orbital overlap and delocalisation. All of these are concepts that are beyond the scope of a standard pre-A level course. The basic principle behind these concepts is that of quantization (of energy, angular momentum etc.), but in terms of the type of descriptions commonly used in A level chemistry the key concept is that of *electron orbitals*. The concept of an atomic orbital - "an allowed wave function of an electron in an atom obtained by a solution of Schrödinger's wave equation", according to one science dictionary (Pitt, 1977, p.30) - is certainly one which learners may find abstract, as Tajinder's comment standing as the motto to this chapter hints.

In the present research it was found that some aspects of the orbital concept gave learners difficulty. The uncertainty about the meaning of electron spin, and the identification of orbital probability envelopes with 'boundaries' were not found to be be serious impediments to progress, but it was also found that

- learners commonly confused hybridized *atomic* orbitals with molecular orbitals;
- had difficulty remembering the designation of atomic orbitals;
- had difficulty understanding the relationship between orbitals, sub-shells and energy levels.

In this chapter aspects of the difficulties with the orbital concept elicited during this research will be illustrated with evidence selected from the database.

§9.1: The quantum hypothesis.

> "you're not going to be able to understand it ... You see, my physics students don't understand it either. That is because *I* don't understand it. Nobody does."
> (Nobel laureate Richard Feynman (1985, p.9) embarking on a lecture on quantum theory.)

A key principle in understanding some aspects of chemistry is that energy, as well as matter, is quantised. This principle may be used to explain the stability of atoms, the existence of discrete energy levels, and the consequent atomic and molecular spectra.

The notion of quantization was introduced as a heuristic device to 'save the phenomena', in that classical physics could not explain the distribution of energy in black body spectra, the sharp spectral lines in atomic spectra, nor the stability of atoms themselves (which as classical electrical oscillators should have radiated the orbital energy of the electron and collapsed to the density of neutron stars). It was accepted that the heuristic device was counter intuitive, so that even Bohr recognised that it required "a conscious resignation of our usual demands for visualisation and causality" (quoted in Petrucciolo, 1993, p.19. C.f. Feynman's warning in the motto above).

To understand the need for such a counter-intuitive hypothesis one needs to appreciate the problems faced by atomic theory before Planck and Bohr proposed quantization. In the present study it was clear some learners did not appreciate why the hypothesis was introduced.

One of the colearners, Edward, understood the consequence of the quantum hypothesis on the transitions between energy levels, as "you could put energy into it, ... and the correct frequency, ... which a particular electron would absorb, it would absorb a photon of energy and be promoted to another vacant orbital". (E2.A203). He also knew "the equation energy equals Planck's constant times the frequency of the radiation" (E2.A252). Despite this apparent understanding of how the quantum hypothesis explained the selective absorption of light, Edward did ***not*** appreciate how the quantization of atomic energies prevented the collapse of atoms. He knew that in an atom there would be forces "between the ... negatively charged electrons and the positively charged ... proton"s (E2.A289), however Edward was not very clear about why this did ***not*** result in the particles moving closer together. For Edward the problem was to explain why the electron was moving in the first place (he suggested that some initial energy was given "in creation", E2.289), but one month from his A level *physics* examination he did not appear to be aware that classically an atom would be expected to radiate energy as an electrical oscillator (see appendix 30, §A30.1.1).

Jagdish was another colearner who did not appear to understand the significance of quantization. In her third interview she stated that "the attractions from the nucleus, pulling in the electrons" were stronger than the repulsions (J3.A460). However she explained that the electrons did not fall into the nucleus, as although "they're being attracted, ... the attraction isn't ... that strong" (J3.A463). However, in the absence of quantization, a weaker net force would lead to a *slower* collapse of the atom rather than no collapse. Presumably Jagdish became aware of this fault in her logic as she comes to a stop part way through her argument, that "if you could actually physically make those electrons get closer to the nucleus then they would fall in because the attraction would be so strong that they'd ..." (J3.A463). She is unable to produce an explanation here that she finds satisfactory.

An example of a learner becoming confused about electronic transitions between orbitals occurred when colearners Kabul and Tajinder were recorded discussing past examination questions, near the end of the first term of the second year of their course. When Kabul attempts to explain thermionic emission in metals he seems to confuse the emission of *electrons* with the emission of *light photons* during electronic transitions (see appendix 30, §A30.1.2).

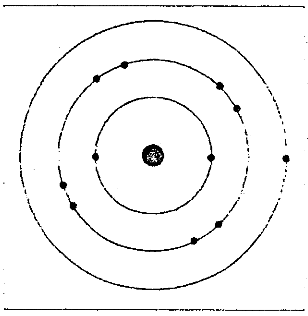
§9.2: The relationship between orbitals, sub-shells, shells and energy levels.

Prior to A level study learners are likely to have considered atomic structure in terms of electron shells. At A level they are expected to appreciate not only the notion of orbitals, but the related-yet-distinct concepts of sub-shells and energy levels. In the present study it was found that learners had some difficulty in making sense of these concepts, and when learners were first told about *orbitals* some of them seemed to take this as a synonym for *shells*, and for *orbits*.

§9.2.1: Learners confused electron orbitals and shells.

So when students are first taught about orbitals, they do not seem to distinguish this new concept from their existing notion of an electron shell. For example, Annie in her first interview referred to "the quantum *shell*, on what the electrons *sit*" (A1.186), and in her second interview to electrons that "go round, like in orbitals, or in spherical things" (A2.378).

Similarly, in Debra's first interview she uses the term 'orbital', although her meaning seems closer to the notion of 'orbit'; so "the orbital closest to the nucleus ... [is] the *path* the electron takes around the nucleus" as the electron "*circles* the nucleus in a sphere" (D1.32-6).

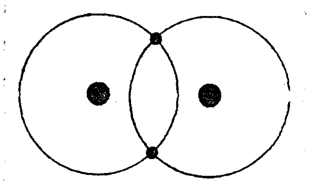


focal figure 1

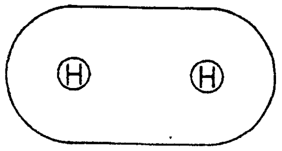
In Edward's first interview (at the end of one year of A level study) he also seemed to confuse shells with orbitals, when he described focal figure 1 (which only showed shells) as a "representation of an atom, with er, its electron *orbitals*, erm in different shells, around the nucleus" (E1.2) and went on to explain that there were three *orbitals* containing two, eight and one electron respectively (E1.4). In his second interview (near the end of his course) he appeared to use the terms 'orbit', 'orbital' and 'shell' as synonyms. When questioned Edward explained that "an orbit's just a circular er thing, ... a kind of neat way of describing an electron's motion" (E2.A050), but that the 'orbital' was "a better way of describing it, [i.e.] to say it occupies a volume - of space ... and there's a probability that it will be found in that volume of space" (E2.A050). (See appendix 30, §A30.2.1.)

In Tajinder's first interview he used the term 'orbital', but also seemed to be using it as a synonym for shell, as "each orbital is like a sphere" (T1.B065). Later in his first term Tajinder undertook Kelly's construct repertory test, and one of constructs elicited by the test was '*shows rough placement of electrons in orbitals*'. A number of triad elements were placed at the explicit pole of this construct, although in most cases what were shown were shells and not orbitals.

Shells and orbitals may be seen as components of distinct models used to discuss atoms. The idea of electron density introduces another variation.



focal figure 2



focal figure 7

Some learners found it difficult to relate their models of electrons in orbits with the notion of *electron density*, as Debra demonstrated when she compared focal figures 2 and 7, which,

> "show different things, but the same sort of bonding. 'Cause [fig. 2] shows the outer shell electrons, erm, *in the path*, but [fig. 7] shows the electron cloud, where the electrons are most likely to be found ... [which is] in the middle"
> D1.306-8.

Yet, Debra explains, the electrons in the cloud are the same ones in "the outer shell" (D1.314) "but they don't always stay there. They're not stationary. They're moving" (D1.318). Debra did not seem to find the apparent contradiction between her interpretations of the two diagrams problematic as "they're both correct ... [but] show different things" (D1.322).

Tajinder's acceptance of alternative, and apparently incongruent, models in chemistry has been discussed in some detail in the previous chapter (§8.4.5). After his apparent confusion of orbitals and shells had been elicited in his first interview (see above) it transpired he had been told something of orbitals in his organic chemistry lesson, (by the other lecturer who taught the class). However when Tajinder attempted to explain the concept it seemed he was not sure what an orbital was, and that he found the idea "hard". (See appendix 30, §A30.2.2).

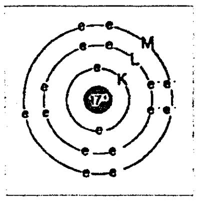
In his second interview, Tajinder continued to demonstrate some confusion over the orbital concept, and its relationship to the concept of electron shells, suggesting that "an orbital is just an area around ... the nucleus of an atom, where electrons are likely to appear, or be held". He initially reported that there would be three orbitals in a sodium atom (T2.A085), before deciding there would be more than three, suggesting there would be "the s orbital, p orbital, d and the f" (T2.A085).

On reflection, Tajinder was aware that he was confusing material presented to him at A level, with his existing knowledge, "what we learnt in G.C.S.E." (T2.A112). Tajinder thought that the rings were "shells" and his G.C.S.E. level model "isn't wrong, but it's not totally correct". However he did not see how the new ideas fitted with the old, and at that time did not think they were related (T2.A123).

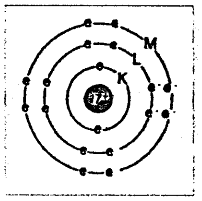
At this point in Tajinder's case his knowledge of electron *shells* seemed to be acting as an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5) to learning about orbitals, rather than as a suitable ***intermediate conception*** on an appropriate ***conceptual trajectory*** (§2.3.10).

§9.2.2: Learners confused shells, sub-shells and orbitals.

Given that some learners had difficulty distinguishing the concepts of *shell* and *orbital*, it is not surprising that the additional concept of *sub-shell* added to the complications. For example, in her third interview, shortly before her final examination, Carol thought there could be eight electrons in the second shell of an atom (C3.387), but this would only require *two* orbitals (C3.389).



triad element 126



triad element 656

During the second term of Kabul's second year he undertook the repertory test exercise (January, 1994). One of the constructs that were elicited was "shows sub-shells", and Kabul construed triad elements 126 and 656 at the explicit pole, as showing sub-shells, although shells - but not sub-shells - were represented. In a subsequent interview Kabul confirmed that he thought the electrons were arranged "in sub-shells" (K5.A049), where "a sub-shell consists of orbitals. Like you know L is a sub-shell consisting of 2p and 2s orbitals" (K5.A077). So at this point Kabul described *shells* as *sub-shells*.

Tajinder made the complementary mistake of describing a *sub-shell* as a *shell*,

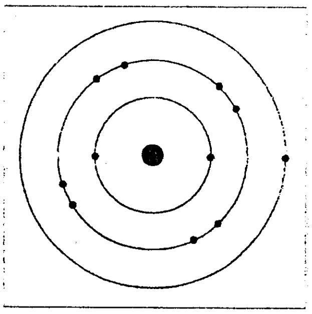
> "if all the orbitals, say the p, p-orbitals are all full of electrons, if you work out where they are most likely to be, erm not sure what the word is, then it will show like a sphere shape of electrons smeared out, so then that is represented by the ... shell, in the diagram that we learnt for G.C.S.E.
> T2.145

§9.2.3: Learners' confusion over energy levels.

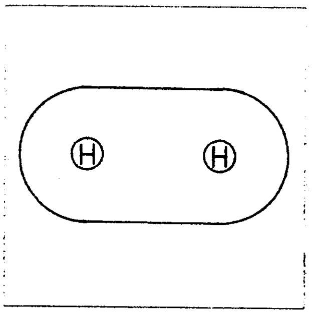
The notion of energy levels provided one further concept to be confused with shells, sub-shells and orbitals.

So, for example, in Annie's third interview (at the end of her course) her explanation of why electrons do not fall into the atomic nucleus invokes *quantum shells*, *energy levels*, *orbitals* and even *hybrids*, without suggesting that she has a clear idea of the distinction between these concepts,

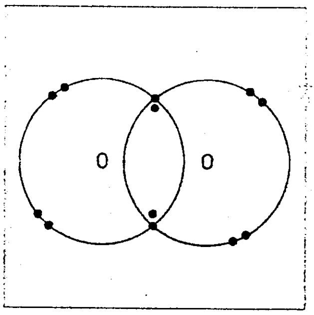
> "The electrons are held in, erm, in *sort of levels*, so, it's to do with sort of bonding, like you can only get two electrons in the first quantum shell. So that they are held in these shells. ... Er, so, they're they're all held in quantum shells which *are* different energy levels, and you can sort of promote electrons should you need to in bonding, so, so if for example you need a bond to have, I don't know, an extra electron in a p orbital, you can donate an s, s electron across, to give you *hybrids, things*."
> A3.10



focal figure 1



focal figure 7



focal figure 4

Carol's first interview took place after one term of A level work had been undertaken, and at this stage she described the lines in focal figure 1, which represented the *shells* of electrons, as the "*energy levels* around an atom" (C1. 18) of sodium. Focal figure 7 was intended to represent the electron density envelope around the hydrogen molecule, but Carol again refers to it as "an energy level" (C1.352) In the second interview Carol showed the same confusion between energy levels and shells, describing how in focal figure 4 the electrons "all look as though they're on the same energy level" (C2.102).

Debra did not seem to relate the idea of energy levels to orbitals. In Debra's second interview she suggested that after a molecule had absorbed light "it's got more energy" (D2.63) and "it's excited the ... molecule and ... [the electrons are] vibrating, and moving more" (D2.69-73). Debra thought this would probably involve *all* of the electrons (D2.75), which normally "move round the, round the nucleus" (D2.77) and "they probably move faster" (D2.79). However Debra did *not* think the electrons would move into a different orbit (D2.83).

In her third interview Debra said it was *not* possible to excite a hydrogen atom (D3.82), and she did not know if it was possible to excite a sodium atom (D3.84). Only when asked to think about 'an experiment, *in physics, not in chemistry, but in physics*, where you have to work out spectral wavelengths' did she describe how "you promote an electron to a higher energy level. ... And then it falls back and gives out the energy" (D3.102-4). It would seem that when Debra was taught about electronic transitions in physics she did not connect this to her work in chemistry (that is she suffered a FRAGMENTATION LEARNING IMPEDIMENT, §1.5.2).

In Tajinder's fifth interview he discussed how an electron could be promoted to an excited state, but he was not sure whether he should refer to the electron moving between shells, or between orbitals. Only after he sketched out his recollection of the diagram he had seen on the board during a class did he conclude that the transitions are between energy levels (See appendix 30, §A30.2.3).

§9.2.4: Learners confused orbitals and probability envelopes.

As some of the colearners in the study tended to think of electron motion in terms of *orbits* it is not surprising that the notion of representing orbitals *of infinite extent* with probability envelopes based on an *arbitrary cut-off* caused some confusion. It is not possible to draw a simple diagram of an orbital, so they are often represented by a probability envelope. By definition there is a small probability that the electron will be found outside *the envelope*, but *the electron can not be outside of the orbital it occupies*. This apparently self-evident statement depends upon a clear distinction between the two concepts (orbital, probability envelope) that the colearners did not always grasp.

Jagdish, in her second interview, referred to *shells* being "just something like arbitrary", before changing this to "*orbitals* were arbitrary" as "they were just regions of space that you had the highest probability of finding the electron" (J2.B218), whereas electron shells "show you the energy levels" (J2.B226). (Although imprecise, Jagdish's explanation shows some increase in sophistication over her first interview when she suggested that on cooling a gas would condense, because "you're stopping *the electrons* from moving around, because you're taking away their energy, so they form a solid", J1.B033).

In his third interview Tajinder also seems to confuse the orbital with the common diagrammatic representations in terms of a probability envelope. Tajinder seems to suggest that the electron is sometimes *outside the orbital*. He thought the orbital was "a probability of finding the electron in that certain area" (T3.A460). Tajinder demonstrated a similar confusion in his fifth interview. He thought that there was "just one" orbital in a hydrogen atom (T5.A433), but that "an orbital just distinguishes a sort of barrier around where you're most likely to find that electron, so it doesn't mean that it just sticks in that one place" (T5.A450). Although Tajinder was informed of his error, in a later interview he referred to how a 2p electron would "come out" of the p-orbital (T6.B090). (See appendix 30, §A30.2.4).

In Umar's final interview for the research, shortly before the end of his course, he described an orbital as the "space *most likely* to contain the electrons" (U4.B291) suggesting that he was also confusing the orbital with the envelopes drawn to represent them.

§9.2.5: Difficulties concerning the designation of atomic orbitals.

For learners who find the *orbital* concept abstract, and confuse it with *shells*, *sub-shells* and *energy levels*, the designations given to orbitals may seem puzzling.

In Carol's final interview she suggested that an s-orbital was an "x, y, z, type of thing" (C3.309) and thought the next orbital to be occupied after 2s was "3p" (C3.365). Edward confused the labels for orbitals and configurations, referring to the atomic hydrogen *orbital* as "$1s^1$" (E1.1050, E2.108).

In Tajinder's third interview he attempted to explain the electronic configuration of an oxygen atom in terms of orbital occupation, but was unsure how many p-orbitals there were in the atom's outer shell (T3.A336). In his fifth interview Tajinder labelled various orbitals with inappropriate designations ($1s^1$, 1p, $1p_x$, $1p_y$, $1p_z$, $3s^1$ and 1d), and did not think that there could be 3s and 4s orbitals (T5.A288). (See appendix 30, §A30.2.5).

§9.2.6: Electron spin.

Electron spin is a concept that is unhelpfully *defined* in one dictionary of chemistry by the statement that "properties of electrons can only be explained in terms of the electrons having spin, $s = \pm 1/2$" (Sharp, 1983, p.152).

However, another science dictionary provides a more helpful explanation, as

> "the intrinsic angular momentum of a subatomic particle, nucleus, atom, or molecule, which continues to exist even when the particle comes to rest. A particle in a specific energy state has a particular spin, just as it has a particular electric charge and mass. According to quantum theory, this is restricted to discrete and indivisible values, specified by a spin quantum number. Because of its spin, a charged particle acts as a small magnet and is affected by magnetic fields."
> (Lafferty and Rowe, 1994, p.556.)

As angular momentum is not a concept that is itself referred to in the A level chemistry syllabus, the concept of electron spin might be expected to cause some difficulties.

In Edward's second interview he referred to electron spin direction, which he 'assumed' meant "that an electron moves about this this volume of space that's called an orbital in one particular direction, whereas the other moves in the opposite direction" (E2.A096), a description which does not relate to a property ***which continues to exist even when the particle comes to rest*** (see above). He had "also read it that they're spinning on their axes", but said that he did not "know what that means" (E2.A096).

In Quorat's first interview she had heard of electron spin, however, her understanding of this term was also based on the everyday meaning of spin as relating to motion, "because they're all going to be repelling each other and circling like that, always trying to get as far apart, 'cause that's why they're always spinning" (Q1.A344).

One colearner who was able to provide an explanation of spin that was nearer the quantum-mechanical meaning was Umar, although he did not seemed satisfied with his understanding. In an interview near the end of the first year of his course he referred to electrons being "spin-paired", and was asked to explain this,

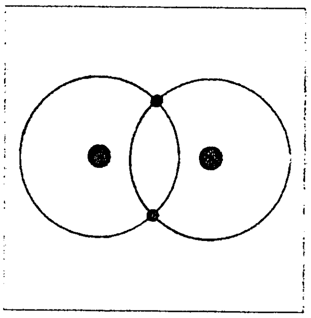
I: What do you mean by 'they're spin-paired'?
U: The the electrons are in same orbital.
I: Ah, what does 'spin-paired' mean exactly?
U: It's just to show that
• • [pause, c.2s]
U: they can be in the same orbital.
I: Ah, but what's all, sorry, what's the 'spin' business? What is the 'spin'?
U: It doesn't actually spin, but
• •
U: (I dunno, I can't remember actually), it's not really spinning itself, but
• •
U: it just means they, they're allowed to be together, I think and, they're in the same orbital, so they might be in opposite directions.
U3.B316

§9.3: Molecular orbitals.

For a learner operating with the notions of shells and electron orbits (see above) bonding electrons may seem to be more confined than other valence electrons, as they must remain in the area of overlap of two shells.

So in Annie's first interview she suggested that electrons in a molecule "move around", (A1.198) except for the bonding electrons, "the ones that are involved in [bonding], they can't really move around, like all the way around the shell" (A1.202). Although by her final interview she was talking of 'orbitals', Annie did not appear to have a clear conception of a molecular orbital,

> "each atom contributes, er an electron, well the electrons are shared equally between the atoms involved, so you haven't got dominance from one atom with the bonds, or of the electrons sorry ... the electrons are sort of held in *circuits, orbitals*, because when they sort of combine together, they're sort of *going around freely*, so you've got all the forces, sort of just like they're being pulled in by the nucleus. Electrons are being pulled in, so you're, you've got sort of the nucleus pulling in, the electrons from the other, atom. So it helps them stay together"
> A4.8-10



focal figure 2

In Lovesh's third interview, near the end of the first year of his course, he suggested that focal figure 2 (representing hydrogen) could be made more accurate if it was drawn with "orbitals instead, 'cause they show the probability of the electron being in that area" (L3.A282). At first he seemed to bring to mind atomic orbitals, and suggested the orbitals "would be sphere" shaped. But then he decided that "they form molecular orbitals", and then suggested that "it would be linear orbital" although he was "not sure" (L3.A282), perhaps confusing the idea of a 'linear *combination*' with the shape of the orbital.

§9.3.1: σ (sigma-) and π (pi-) bonds.

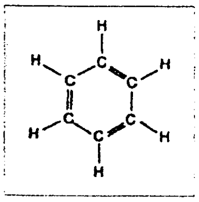
Where learners *were* able to discuss molecular orbitals appropriately, one area of difficulty was the categories of sigma and pi bonds.

Paminder used the construct 'pi-bonds' in Kelly's construct repertory test, and she was asked about this during the second interview. Paminder knew that a pi-bond differed from a sigma-bond, but was unable to offer any detail of what the pi-bond was, except that it was "like a hamburger" (apparently in terms of sandwiching the sigma bond),

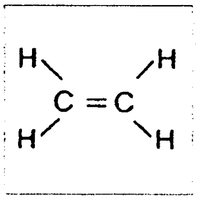
> "when you have something with a double bond, like say for example, ... suppose you have carbon-carbon double bond, like an alkene, yeah? Like this is all *to do with orbitals and things*, like, suppose we have ethene, which is C double bond C, H H H H, and like, this, *we're talking about orbitals now right*, when the double bond is formed it's like an actual pi-bond is formed, *it's not like a sigma bond*, a sigma bond is like just simple overlap of like the orbitals. A pi-bond is *slightly different*, it's like, it's like a hamburger you could say. {Both laugh}. You know like, this pi-bond like, if you look at the molecule like, three dimension, I think it's three dimensionally yeah? There's a pi-bond on top, pi-bond cloud there, pi-bond cloud there, that's the kind of thing."
> P2.A327

She thought that a "sigma bond, ... [is] just a simple overlap of like atomic orbitals" (P2.A327), and later added that "it's just linear overlap, like I think, if it's in the same plane, or something, something like that" (P2.A349). Although Paminder was thinking about bonding in terms of orbitals and orbital overlap, her understanding of molecular orbitals may be seen to have been tentative.

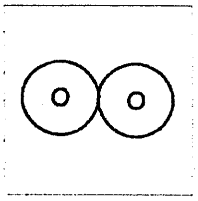
Another colearner to use the construct 'pi-bond' was Edward.



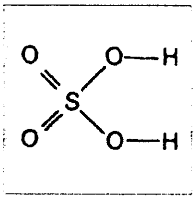
triad element 414



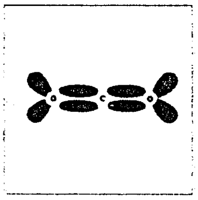
triad element 211



triad element 245



triad element 443



triad element 522

During the first term of the second year of his course he undertook the repertory construct test. Some of his assignments suggested that his understanding of pi-bonding was either confused, or idiosyncratic. He construed triad elements 414 (benzene molecule), 211 (an ethene molecule) and 245 (an oxygen molecule) at the emergent pole of either of his construct "pi-bond", although *not* triad element 443 (a molecule of sulphuric acid, with double bonds indicated as S=O), nor triad element 522 (a carbon dioxide molecule).

In Lovesh's final interview, shortly before the end of his course, he discussed the bonding in benzene where he thought there was "covalent bonding, and there's *also* some delocalisation". For him this meant "each carbon atom has got an unhybridized p-orbital with an electron in it and that form ... *two pi-bonds,* and that's where the electrons can move around, in a pi bond" (L4.A424).

Lovesh thought the pi bonds were "above the ring and below the ring", and these were two separate bonds "one above and one below, the ring" (L4.A424). In other words, Lovesh was considering the two different volumes of electron density as being two separate bonds.

§9.3.2: Atomic orbitals, hybridization and molecular orbitals.

In molecules the bonding electrons are considered to be in molecular orbitals which are formed by overlap of, and linear combination of, atomic orbitals. Often, although not always, the atomic orbitals involved are considered to be hybridized from the ground state atomic orbitals. (Electrons from inner atomic shells, and non-bonding electrons from the valence electron shells are usually considered to effectively remain in atomic orbitals.) In this research it was found that there were many examples of learners apparently confusing *ground state atomic orbitals, hybridized atomic orbitals* and *molecular orbitals.*

The hybridization process is considered to provide combinations of atomic orbitals with a more suitable geometry for overlap, so as Carol explained about p orbitals, "you hybridize them because you've got half of the, the p-orbital out the other side where you don't need it" (C3.455), otherwise there might be a "bit of a waste" (C3.507) because "you've got half of it not being used" (C3.509). hybridization is often accompanied by unpairing of electrons to give a greater number of half-occupied orbitals for overlap, an aspect that Carol seemed less clear about,

> "something about, [when there is a] load of electrons say all together, and you, split them all up. So ... say in, group five you've got five different electrons ... in their separate, little bit. So ... other electrons can come and *bond* [sic] with them, 'cause they've got a space ..., 'cause they're not spin paired."
> C3.515

In the study there were examples of colearners assigning *ground state atomic orbitals* to *molecular orbitals.* In his first term Tajinder undertook Kelly's construct repertory test (November, 1992), and one of the constructs elicited was 'shows s and p orbitals'. However, most of the triad elements construed at the emergent pole actually represented molecular orbitals.

In Paminder's third interview, near the end of her first year of A level, she suggested that in a hydrogen *molecule* the electrons would be in an "s orbital" (P3.A379) and in a tetrachloromethane *molecule* the electrons in a bond were in a chlorine "3p" orbital, and a carbon "2p" orbital (P3.A387). Paminder thought that the four carbon bonding electrons were in the $2p_x$, $2p_y$ and 2s orbitals, and indeed that *two* of the bonding electrons, i.e. in two different bonds, were in "the 2s" orbital (P3.A403).

Although in real chemical systems promotion of electrons, rehybridization of atomic orbitals, and formation of molecular orbitals are not discrete processes, they are usually presented as if discrete when formulated as a conceptual scheme. Despite this learners may confuse the ideas of *rehybridized atomic* and *molecular* orbitals, as when Brian referred to "the bonding sp^3 hybrids" (B3.690).

At the end of his first year Lovesh referred to molecular orbitals in tetrachloromethane and methane, as hybridized atomic orbitals, and during his second year he suggested the presence of atomic orbitals in molecular systems (graphite, benzene) where those orbitals would have been 'used' in the bonding (see appendix 30, §A30.3.1).

This type of error could occur even when a learner had demonstrated a grasp of the principles involved. So although at the end of her course Debra demonstrated that she understood the concept of molecular bonding in the simple case of the hydrogen molecule (see appendix 30, §A30.3.2), she thought that the bonding electrons in benzene were "in molecular orbitals" (D3.518) which were "hybrids" (D3.520).

Similar data was obtained from Edward who was able to explain the electronic configuration of carbon, and the process of hybridization ("where you put energy into the system, in the hope that, you'll get a more stable resultant, structure", E1.884), but did not seem to appreciate the formation of molecular orbitals from overlap of atomic orbitals (see appendix 30, §A30.3.3).

A different error was to assume atomic orbitals *always* need to be rehybridized to form bonds. So near the end of her course Carol described a π bond as "overlapping of p-orbitals" (C3.297), and in the specific example of the oxygen atom in forming an oxygen molecule, she suggested the hybridization would be "π [pi], hybridization, ... or something like that" (C3.295). Carol thought that "you have to hybridize them otherwise they don't overlap fully" (C3.299), not realising that this particular bond was formed by the overlap of *unhybridized* atomic orbitals.

Some of the difficulties experienced by learners may be illustrated though the example of colearner Kabul (see appendix 30, §A30.3.4). At the end of his first year he demonstrated that he understood the basic notion of hybridization. However at the end of the first term of his second year Kabul undertook a College test on multiple bonding and explained the bonding in carbon dioxide in a way that was not only incorrect from the CURRICULUM SCIENCE perspective (with the wrong hybridization on the carbon) but which contained internal contradictions - the same orbital being described as both p-orbital and hybrid - that make it difficult to produce a consistent interpretation of Kabul's thinking. It seems likely he was himself unsure of a coherent scheme.

When he undertook the repertory test during the second term of his second year Kabul construed molecules as having "sp^3 hybridization", assignments he confirmed during a subsequent interview (K5.A331). When he was asked about hybridization he explained that different combinations of orbitals could be hybridized, although he put this down to "what they *want* to form" (K5.A356). (Learners' use of anthropomorphic language is considered in chapter 11, §11.3). When he was asked about forming the ammonia molecule Kabul was confused about the hybridization required on nitrogen, the number of hybrids formed by the sp^2 and sp^3 hybridization, and suggested that in each case one hybrid would be "not that similar" to the others. Kabul appeared to be confusing the nitrogen ***atomic hybrid*** containing the lone pair, with the ***molecular orbitals*** formed from the overlap of the other hybrids with the hydrogen atomic orbitals. Although Kabul seemed to have some grasp of the key points of the hybridization concept, particularly the requirement "to get good overlap", he also showed some confusion. It would seem he had still not completely separated the concepts of the hybridized atomic orbitals from the molecular orbitals that resulted from overlap: thus the suggestion that one of a set of hybrids would be dissimilar because it contained a lone pair.

This issue was further explored later in the fifth interview (see appendix 30, §A30.3.5). During an extended exchange Kabul's belief that the atomic orbitals still exist in molecular species was elicited, and then challenged. Kabul thought that the orbitals present in the hydrogen molecule were "s orbitals, 1s orbitals", none others, "just 1s orbitals" (K5.A420). In methane he thought there would be "1s and p orbitals ... like 2p on carbon, and 1s on hydrogen" (K4.A424). Indeed Kabul at first suggested that on carbon there would be not one p orbital, but "four, $2p_x$, $_y$ and $_z$, ... four [sic]" 2p orbitals (K5.A428). As well as these 2p orbitals, he thought that "there are [other orbitals on carbon] but they're, they don't take part in bonding" (K5.A428).

When Kabul was asked about methane he seemed to confuse two aspects of the hybridization process (the geometry and orientation of four similar sp^3 hybrids that makes them suitable for overlap with orbitals on other species, and the similarity of the energy levels of two overlapping atomic orbitals that leads to a molecular orbital of significantly lower energy). Although Kabul had talked of the overlap involved in forming bonds, he then went on to describe the orbitals present as *atomic* orbitals.

When he was asked about diamond Kabul first suggested there were only ground state atomic orbitals present, but he later changed this to include hybridized *atomic* orbitals.

When it was put to Kabul that there were no 1s orbitals in the hydrogen molecule, and no sp^3 hybrids in the methane molecule, he did not agree. Only after agreeing that there was a molecular orbital present (which he recognised was "made up of, ... two atomic orbitals, [which] combine together to form a molecular orbital" , K5.A487) did Kabul *then* agree that there were no 1s orbitals in the hydrogen molecule.

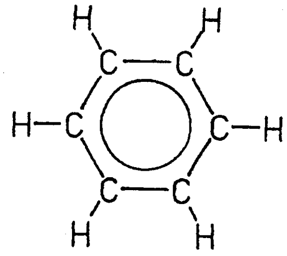
However, when asked about the methane molecule again, it took Kabul a short time to transfer the same argument to this context, and agree that there were no (valence shell) atomic orbitals in the methane molecule. After this though he did immediately recognise that he was wrong about the hybridized orbitals in graphite: that in the structure there were actually molecular orbitals. In this interview Kabul had demonstrated that he had both the necessary knowledge, and the competence, to discuss the orbitals present in hydrogen, diamond and methane from a molecular orbital perspective - one might say such a description was within his ***zone of proximal development*** (§2.2.2) - but that he spontaneously tended to think of the molecules in terms of the atomic orbitals present before bonding. His knowledge of atomic orbitals and hybridization seemed to act as an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5) to thinking about molecular orbitals.

§9.4: Resonance.

Some structures of interest to chemists cannot be readily represented in terms of drawing single, double and triple bonds between specific atoms. These structures are often better represented in terms of a molecular orbital description. However, it is usually also possible to consider the actual structure to be 'in between' a number of valence-bond structures, called canonical forms. The actual structure is said to be a resonance of these canonical forms.

In the present study there was evidence of learners having difficulty conceptualising resonance. In particular there was evidence of students considering the resonance to mean an alternation between the canonical forms, rather than something intermediate to them.

§9.4.1: Resonance in benzene.



focal figure 12

In the interview study a range of interpretations of the bonding in benzene were elicited from colearners, and - as would be expected - individual colearners' understandings changed over time. Three themes may be identified from the comments made. The first theme is that of the interpretation of the circle used to represent aromaticity, which was seen by some colearners as indicating some type of *electron reservoir inside the ring*. A second theme concerns the use of the term *delocalisation*, but in the absence of a molecular orbital interpretation that makes the notion vague, and even unrelated to the bonding. Thirdly, although learners may refer to resonance, they may mean an *alternation* between single and double bonds, although perhaps one which occurred very rapidly.

These three themes may all be illustrated in the case of Annie. In Annie's first interview she thought that the circle "shows where the electrons are, because it's electron rich" (A1.464) and "they're denser in the circle" (A1.466) - not all the electrons - "just the ones from the carbon" (A1.472). In her second interview

Annie showed an awareness of delocalisation, although this did not appear to be related to any concept of molecular orbitals. Her interpretation was that the electrons "go around in the ring, so they sort of charge around and, ... they're not fixed anyway, they don't belong to anything in particular, so they're, they're free-flowing" (A2.295).

In the third interview Annie demonstrated some notion of the resonance, in terms of single and double bonds that move around the ring,

> "If you've got the benzene ring, erm, with the double bond and the single bond and then, I don't know somehow, a simplistic way of looking at it, and the bond moves, ..."
> A3.233

Each of these three interpretations were reflected in data from other learners.

The electron reservoir. Where Annie referred to a circle "where the electrons are, because it's electron rich" (A1.464), in Brian's second interview he demonstrated a more technical rationale for a similar interpretation. He took the circle *inside* the hexagon as a literal representation of where the delocalisation occurred (B2.58-60). Brian reported that the p-orbitals "of the ring overlap, and the electrons can pass from orbital to orbital, to become delocalised" (B2.76), but he though that the p-orbital used to overlap to give the delocalised system was *in the plane* of the ring, so "in carbon there's four valence electrons, three of which are used in bonding, and the one in the other p-orbital" (B2.76) which was in "the plane of the" hexagon (B2.82).

Carol's interpretation in her early interviews was less technical, in terms of spare electrons. So in her first interview she explained that "there's six *spare electrons* in the middle" (C1.579), which were "just spinning around" (C1.581). There were spare electrons as "carbon, it's got a valency of four, and, because it's only got three ... bonds ... , it's got to have one [electron] still whizzing round itself" (C1.585-587). She thought that these 'spare' electrons were "attracted to their own nucleus" (C1.623) and were localised (C1.625). In her second interview Carol maintained that in benzene there were "spare electrons from the carbon" (C2.452) "because carbon's got a valency of four so it can form four bonds and yet it's only formed three, so they're, like, left in the middle" (C2.454) She thought that the 'spare' electrons were not involved in bonding, and "you show that by the circle" (C2.456).

In Debra's first interview she had a similar interpretation, that the circle was "where the *extra electrons* are from the outer, shell. 'Cause it usually has a valency of four, [so] there's one electron from each carbon, in there" (D1.504). She thought that these extra electrons were "sort of free to move ... in between carbons"

(D1.510-512). Even in her second interview, when she was considering the resonance as between single and double bonds, Debra thought that the circle "shows the electrons" (D2.423) which are "sort of, *within* the carbons, *within* the ring ... Or *in the middle*" (D2.425-7). She was able to explain the hybridization in the molecule, and the overlapping of the unhybridized p-orbitals, but despite this, Debra still thought that the ring drawn in diagrams of benzene represented the "*spare* electrons" (D2.605).

Kabul demonstrated a sophisticated interpretation of the circle, that it represented "the electron density, of carbon atoms" (K6.A557), which was shown for benzene "because ... the outermost electrons [from "just the carbon atoms" (K6.B004)] are equally attracted by the whole ring of atoms, not just one atom" (K6.A562). However, even here the circle symbol appears to be taken too literally, as the electron density represented is *actually* above and beneath, *not inside*, the hexagon.

Vague notions of delocalisation. Annie's notion of delocalised electrons not belonging [sic] to anything, not fixed to anything and free-flowing (A2.295) does not make sense from a valence-bond perspective, and was not supported by any kind of molecular orbital interpretation, but rather seemed to have been learnt as an isolated piece of information (c.f. FRAGMENTATION LEARNING IMPEDIMENTS, §1.5.2). Although Annie had also learnt that the circle could indicate "an unsaturated, aromatic or something" (A2.287), she thought *aromatic* simply meant "that it smells" (A2.289).

During Brian's first interview he demonstrated that he had acquired the notion that benzene had "a delocalised system" (B1.434), but he thought this just meant meant that "the double bonds aren't in any set place ... they're not in specific places on every benzene ... molecule" (B1.436-440). In Carol's final interview she described the benzene molecule as having both rings of electrons, *and* delocalised electrons, that is "kind of like a ring [with] like electron thing underneath it, and electron thing on the top, isn't it, because they're π-bonds ... and then you've got delocalised electrons in the middle, but I don't know what they look like" (C3.1019 -1021). She later she referred to the 'electron thing' as "the electron density below and above it, kind of thing" (C3.1037), however she did not realise that this 'electron density' *was* the delocalised electrons. Whereas the electron density was 'underneath' and 'on top', the delocalised electrons were inside the ring, and were not seen as relevant to the bonding.

In Kabul's last interview he referred to how "the electron density ... [of the] carbon atoms, overlap with one another, and they form a delocalised structure" (K6.B031).

However his explanation of this delocalisation was simply that the three electrons from each carbon atom involved in carbon-carbon bonding were "attracted equally between carbon atoms" (K6.B041).

Resonance as alternation. In Annie's second interview she was unsure about the existence of double bonds in benzene, first suggesting that benzene had "single" (A2.277) "covalent bonds" (A2.275), although "one carbon to carbon bond would be a double bond" (A2.279), and then that "they're *all* single bonds" (A2.281).

Although Annie referred in her third interview to "the double bond and the single bond and then ... the bond moves" she recognised that this was "a simplistic way of looking at it" (A3.233). Annie was aware that the canonical forms were not accurate representations of the structure of benzene - as "they don't really exist, it's sort of something that scientist has in their minds to show, to explain something", and "in nature, they don't actually perform that way". However, Annie did not seem to consider the role of molecular orbitals, and was limited to discussing benzene in valence bond terms ("you haven't got single bonds all the way around, you've got to have three double bonds"). (See appendix 30, §A30.4.1).

In Brian's first interview he seemed to imply that single and double carbon-carbon bonds were fixed in particular molecules (although "the double bonds aren't ... in specific places on every benzene ... molecule" (B1.436-440). Carol however clearly entertained the notion of alternation of the bonds within the molecule. In her final interview, *as well as* discussing the electron density above and below the ring, and the electrons inside the ring, she *also* talked of how,

> "it will be double bond, single bond, double bond, single bond, double bond, single, ... and, to make the resonance, you draw a little two way arrow, and where there was a double bond in one diagram there would be a single bond in the other one."
> C3.1047-9

Carol seemed confused over these three different models (the spare electrons, the π clouds and the alternating single/double bonds), and immediately after referring to the double bonds suggested there were "just single bond all the way around, and the delocalised electrons in the middle, in a ring" (C3.1051). She also thought that the bond order "could be any, anything you wanted to" (C3.1051). She went on to suggest an alternative interpretation of the circle in the figure: that it "shows that, you can either have a double bond, or a single bond, and it happens so quickly that you might as well just have a single bond" (C3.1057), but although the alternation was rapid, she thought it was literal, so that the bonds were actually "both ... sometimes single, sometimes double" (C3.1060-1061).

By Debra's second interview she was referring to resonance in benzene in terms of an alternation, so that - of the carbon-carbon bonds - "some of them are double and some of them single, ... there's three that are doubly bonded, but the electrons are free to move between, between the carbons so you don't actually write on the diagram as a double bond" (D2.391-393).

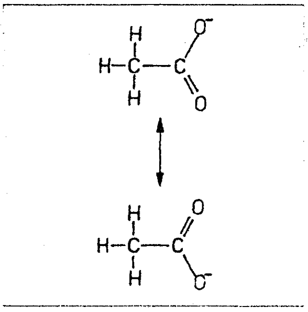
However, she contradicted this view of alternating bonds when she went on to suggest that the bonds were "in between the length of a single and a double" (D2.403) and that the bonds were ***not*** single or double but "midway between them" (D2.411) - although Debra could only suggest this might mean "three" electrons per bond (D2.417). By this interview Debra had some understanding of hybrid orbitals. So whereas in preparing methane "you hybridize" the carbon orbitals (D2.464) to give "four" (D2.470) "sp^3" hybrids (D2.466), which point in a "tetrahedral" arrangement (D2.474), in benzene each carbon atom has to bond with "three" other atoms (D2.493), so the hybridization required would be "sp^2" (D2.497), which leaves "a p orbital" (D2.501), where Debra supposed "the electrons are [in an] overlapping p-orbital so they're paired" (D2.679). However, Debra did not seem to be able to integrate her consideration of the single and double bonds with this discussion in term of orbitals.

Kabul's explanation of the bonding in his final interview also demonstrated some ambiguity. He knew that each carbon atom would "use one of its electrons to form bond with the hydrogen, uses one of the bonds [sic] to form bond with the carbon, another carbon, and uses two of its electrons to form bond with another carbon" (K6.B018.) Kabul also seemed to recognise that delocalisation gave rise to a symmetrical distribution of electron density, but he did not seem able to explain how this *related* to the valency requirements of the atom,

> "the actual structure of benzene, you know, where you've got a single bond, double bond, single bond, double bond, alternating ...But, but when you see it overall, ... the electron density ... [of the] carbon atoms, overlap with one another, and they form a delocalised structure."
> K6.B031

During Quorat's second year she prepared a concept map for 'multiple bonding' as a revision exercise. This map included a reference to "resonance structures" and "canonical forms" (see appendix 30, §A30.4.2). However her explanatory notes suggested that Quorat construed 'resonance' as a device for overcoming ignorance about which bonds were double and which were single ("since the actual positions are not known, it is better shown as a delocalised system"), rather than as a means of representing bonds with non-integral bond order, e.g. those which were between single and double bonds.

§9.4.2: Resonance in the ethanoate ion.



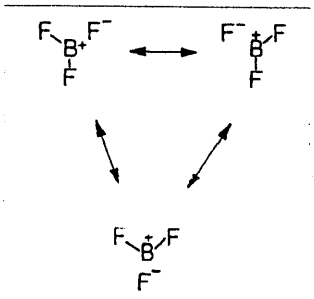
focal figure 13

Focal figure 13 was intended to represent the two canonical forms for the ethanoate ion. In Debra's first interview, she thought the two canonical forms were the same molecule seen from a different angle (D1.574), as she did not think the same molecule could change between the two configurations (D1.578). However in her second interview she had changed to a more common interpretation in terms of alternation between the two structures. Debra suggested that the double headed arrow in focal figure 13 "represents that it can change from one to the other" (D2.689) when "the electrons that are in, that double bond, move over to the other carbon and the oxygen, and form a double bond there" (D2.693).

In Brian's second interview he identified that the arrow meant "resonance between the two forms" (B2.106). He recognised that in the two different forms shown a "different oxygen" centre was charged (B2.114), although he thought resonance meant "it alters between the two states" (B2.110) so that at any one moment an oxygen "could be minus, or it could have no charge" (B2.145), but the change over was "instantaneous" (B2.156). By his third interview Brian's thinking had developed further to match the intended meaning of resonance, so he thought that the arrow represented "resonance" (B3.286) which meant that "it exists sort of between the two forms" (B3.288), the bond order was "one and a half" (B3.298), and the molecule would exist in a "form in between [the canonical forms] with, single bonds to both oxygens and a delocalised system between the two oxygens" (B3.322) comprising of "overlap of p-orbitals" (B3.324-332) on the carbon and both oxygens.

Kabul also developed beyond seeing the resonance as alternation, although his thinking did not shift as far as Brian's. In Kabul's fourth interview he thought that "the negative charge is being shared you know by both the oxygen atoms" (K4.B330). This was according to "something which [Kabul had] read", but he could not "recall now" (K4.B330). However, he thought the arrow symbol was meant to represent "resonance" which meant "sometimes it could be this thing, sometimes could be the bottom thing" (K4.B346), although he could not suggest how this could be. However, in his final interview Kabul explained that the diagram showed "a resonance between ... two forms of a compound" which meant that "it can either exist in this form or other form, you know, the actual structure is in between both the forms" (K6.B056). Kabul agreed that he *was* saying that the structure swaps round between the two, so at any one moment it could be one, then it would flip over to the other one (K6.B063). As he seemed to be implying an alternation of the structure Kabul was asked what he meant by saying that the actual structure is between the two. He explained that "the electron cloud will be shared equally between ... two oxygen atoms, so that's the actual structure" (K6.B066). So Kabul appeared to hold two distinct models of the structure in his head, one with a stable smeared electron density, but the other involving alternation between valence-bond structures such as those in the figure he had been shown.

§9.4.3: Resonance in boron trifluoride.



focal figure 14

A third context for discussing resonance was that of boron trifluoride. The focal diagram (number 14) showed three canonical forms, each with two covalent bonds and one ionic. This is one mode of representing the bonds as polar.

In the first interview Brian describes the diagram as depicting "an alternation between the states of boron fluoride" (B1.539). He identifies the bonds present as "ionic and covalent" (B1.541): so "the majority of the time [a particular bond] is covalent, but occasionally it is ionic" (B1.560). In his second interview the polar bonding in boron trifluoride was thought to consist of "some covalent, and some ionic" bonding (B2.122), and Brian thought the electron density distributions would be different in the two types of bond (B2.137-139). In the third interview Brian describes the bonding as "sort of fifty-fifty ... co-ionic ... [or] polar" (B3.434-8).

Although Brian reports that "all three of" the bonds will be polar (B3.442), as "they'll all be the same" (B3.444), he describes the electron density in terms inconsistent with such a belief,

> "polar towards the fluorine ... *on the two* ... fluorines that are not charged. There will be a greater electron density around the fluorine. And *on the one* that is charged it will be completely around the fluorine."
> B3.452

Brian's explanations are contradictory, as he ***subsequently*** maintains that all the bonds are equally polar (B3.470). In this less familiar example of resonance Brian does not seem to fully appreciate the way canonical forms showing ionic and covalent bonds are able to stand for a resonance that does not alternate between them, but rather has a form 'in between' them. He apparently interprets the bond type differently depending upon whether he is labelling the bonds verbally, or construing them in terms of electron density patterns, an interesting finding which mirrors Kabul's distinct conceptualisations of the ethanoate ion structure above (§9.4.2).

In Debra's first interview she did not recognise the resonance represented in focal figure 14, but instead interpreted one of the canonical forms literally: that there were "two covalent bonds, and one ionic bond" (D1.624).

In Kabul's fourth interview, he was asked to consider the diagram, which he thought showed that "sometimes, one of, this fluoride ion is negative, so sometimes this fluoride, another fluoride ion can be negative. It shows like resonance" (K4.B381). The CURRICULUM SCIENCE meaning of the term resonance would be that all three of the bonds were something ***in between*** ionic and covalent, but further questioning suggested that this was not what Kabul meant (see appendix 30, §A30.4.3). Although Kabul referred to resonance, his spontaneous ***expectation*** was that the bonds would be covalent (K4.B377), and his interpretation of the figure was that individual bonds would at any one time be covalent or ionic.

In his final interview Kabul thought that the figure represented "resonance" which meant "it can exist in either [sic] form. It can be either of them, at any time" (K6.B084). Kabul thought that the diagram probably meant that "it's bonded covalently with two and ionically with one" (K6.B096). Changing between the different forms required the "atom" to "just flick around" (K6.B102). So even near the end of his course Kabul did not consider the CURRICULUM SCIENCE meaning of the resonance.

This particular example, representing polar bonds as a resonance, may demonstrate something more than a difficulty with a molecular orbital description, as it will be suggested in chapter 11 that learners in this study commonly showed some reluctance to label bonding as intermediate to ionic and covalent (§11.6.2).

Chapter 10.

Learners' alternative conceptions of electrostatics forces.

§10.0: The significance of learners' notions of electrostatics.

As progression was found to be related to the adoption of electrostatic principles as the basis of explaining bonding phenomena, learners' notions about electrostatic forces are of central importance to the research. In this research the colearners exhibited beliefs about the interactions of charged particles which are inconsistent with Coulombic electrostatics, and may therefore act as impediments to the learning of the curriculum science model.

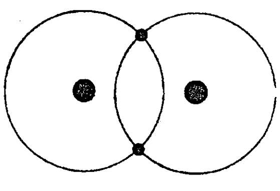
It was found in this study that most of the chemistry learners interviewed exhibited notions about the interactions between charged particles which were in some sense inconsistent with CURRICULUM SCIENCE The following features were found amongst one or more of the colearners in the study,

- an interpretation of charge as a deviation from full electron shells, rather than a deviation from electrical neutrality.
- apparent confusion of force with charge.
- apparent confusion about force and energy.
- systems were considered to be in equilibrium without forces being balanced; or to be non-equilibrium systems when forces *would* cancel.
- forces were associated with one body, not seen as an interaction between bodies.
- forces were seen to act from one charged particle onto another, without reciprocity (as required by Newton's third law). The 'reaction' forces might be absent (or considered as negligible), of the wrong sign (i.e. an attraction paired with a repulsion), or wrong magnitude (i.e. the greatest force acting on the smaller particle).
- nuclei were considered to give rise to a fixed amount of attraction - depending upon charge - which would be shared amongst the electrons available to receive it.

These alternatives to conventional electrostatic principles were found to varying extents (for example the 'deviation charges' notion was only elicited from Annie, but the notion of the effects of a charge being shared was more common.) Some learners were found to apply different variants of physical principles in contexts that were equivalent from a CURRICULUM SCIENCE perspective. Similarly the meanings that learners appeared to give to words such as 'force' and 'attraction' did not always match the CURRICULUM SCIENCE definitions. These aspects will be considered, and evidence presented from the data base.

§10.1: Ignorance of electrostatic forces.

The case of Annie has been discussed in an earlier chapter (chapter 7), and her alternative conception of charge, DEVIATION CHARGES was described (§7.2.2). Although Annie saw charge as a deviation from noble gas electronic structure, and therefore classed neutral atoms as charged, she believed that there would be a force between two particles that were charged in her scheme. For example, a sodium atom and a chlorine atom "would probably get held together by just forces" (A1.256). The force was, "the attraction from the plus to the minus because like *chlorine's minus an electron* and *sodium is over an electron*" (A1.260). The force was seen to be a direct consequence of the deviation from a stable electronic structure, that is (in her interpretation) the lack of, or abundance of, electrons (see appendix 31, §A31.1.1). So for Annie it was not *electrostatic charges*, but DEVIATION CHARGES which gave rise to a force. Although Annie's DEVIATION CHARGE conception was unique amongst the co-learners in the research, Kabul also commenced A level chemistry apparently ignorant of electrostatic forces.



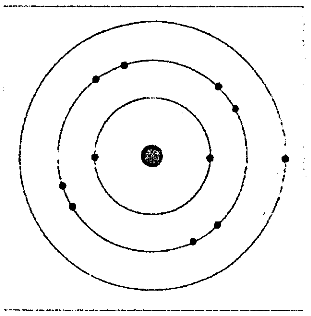
focal figure 2

Kabul thought there was a force involved in holding the atoms in focal figure 2 together. However, he was unable to suggest what physicists might consider to be the basic forces. He recalled that "there is force like gravitational force" but he did not think that this was involved in holding atoms together (K1.B165). That force was different as "gravitational force is due to the force of gravity. But ... [the force between two atoms] is an attraction force" (K1.B165). Kabul thought that gravity was "not an attraction, it just pulls everything downwards" (K1.B165). Kabul knew about the tides, and they were due to "the attraction from the moon", but he had "no idea" what kind of attraction that might be - except that it was not the same attraction holding the atoms (in focal figure 2) together, and (three centuries after Newton proposed Universal Gravitation) nor did he think it was the same kind of attraction that makes an apple fall from a tree (K1.B191). As well as these three types of force Kabul suggested that there were "lots of forces", and they all had to be treated separately (K1.B191).

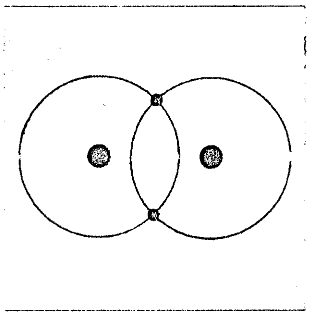
§10.1.1: Learners may confuse force with charge.

An example of a colearner who appeared to have an alternative meaning of the word force was Jagdish. In her first interview she suggested that "the proton ... has a stronger force so there is a kind of *positive force* ... at the nucleus" (J1.A076), an utterance which suggested that Jagdish did not always use the CURRICULUM SCIENCE distinction between 'force' and 'charge'. Her utterance seems to imply either that force *is* charge, or that it is a property of charge (rather than arising between several charges). The notion of force being designated to charged particles is discussed further below (§10.3.4).

In her second interview there were other utterances which suggested that Jagdish was not using the conventional idiom of CURRICULUM SCIENCE The discussion had turned to electricity and in order to find out what Jagdish meant by the term she was asked about 'anti-iron' which she thought would contain delocalised positrons. Jagdish would not commit to whether electricity would be possible, but one would "have some sort of erm, *force* like electricity" (J2.A206). She was asked about a radioactive substance giving out a stream of alpha particles, and she thought that this was "maybe not electricity as we know it, but ... it would, be a *force* though ... *it is a force*, but I, you wouldn't call it electricity" (J2.A224). Jagdish said she had used the term *electric current* at G.C.S.E., where it was defined as a "flow of electrons" (J2.A240). In this sense a flow of alpha particles was "not electricity, but it is a current", and Jagdish went on to suggest "*it is a force*, because it's charged ... so there must be a force" (J2.A240). When it was suggested to Jagdish that perhaps the definition she had been given (*i.e.* that to be a current there had to be a flow of *electrons*) did not cover all cases, she seemed to accept this this readily, as "it's all *energy* though, isn't it, I mean like a flow of electric current, or a flow of alpha particles? It's all *energy*. It's all some sort of *energy*" (J2.A240). It would seem that for Jagdish an electric current, electricity, was not a phenomenon that was *related to* force and energy, but rather that electricity *was* a force, and *was* energy: She did not apply the distinct meanings that scientists give to these terms. In particular she seemed to think that the presence of charge implied a force, where the CURRICULUM SCIENCE view would be that the force arises from the interaction of different charges (c.f. §10.4 and §10.5).



focal figure 1



focal figure 2

In Quorat's first interview she did not seem to consider that an attraction counted as a force,

I: Are there any forces in, in number 1, would there be any forces, or interactions?
Q: No.
I: No?
Q: No, it's just the electrons *attracted* to the positive nucleus, that's why they're kept together.
I: Right, but there's no force though?
Q: No.
I: They're just attracted?
Q: Mm.
Q1.A226

Later in the interview Quorat referred to "the force of the nucleus" as if it is a property of the protons. So in focal figure 2, representing the hydrogen molecule, the strength of the force depends upon "the force of the nucleus" which is due to "the positive protons" (Q1.A381). She explains that "the more positive it is, ... the more the force it will put onto the electrons, so the more they'll be attracted to the nucleus" (Q1.A380). In focal figure 1, the force on the electrons depended on two factors, "how further [sic] away the electrons are from the nucleus, the distance" and what Quorat called "the force of the nucleus, how positive it is" (Q1.A386, c.f. §10.5).

In Tajinder's second interview he suggested that in metals "one of the forces might be *positive and negative forces* that hold them together" (T2.A207). Tajinder repeated that there were "positive and negative forces" which were "not the same". However he did not appear to mean the convention that repulsive forces are given a positive sign, and attractions a negative sign, rather, he was confusing force with charge, so that "two *positive forces repel* one another, and so do two *negative forces repel* one another, but *opposite forces attract* one another" (T2.A207).

So in the present study, as in the literature reviewed in chapter 3 (§3.1.3), learners do not always use the term *force* in its CURRICULUM SCIENCE sense.

§10.1.2: Learners may confuse force with energy.

Another finding of the present study that reflects the existing literature is that learners did not always seem to clearly differentiate the concepts of 'force' and 'energy'.

So in her third interview Carol seems to conflate force and energy when she describes "that Coulomb's, thing" (C3.689), that "the further they are away the less ... kind of *energy* they have *against* the other one" (C3.691). In Mike's first interview he explained the attraction between an electron and a nucleus as "positive-negative *energy* attracting ... positive *energy* coming from the, the nucleus, and negative *energy* from the electron" (M1.A163)'. When he was asked about force he suggested that he "knew some of the forces, [e.g.] kinetic, potential" (M1.A163), i.e. labels that in CURRICULUM SCIENCE refer to energy, not force.

Potential energy is important because energy changes met in chemistry usually involve changes in electrostatic *potential*. Kabul did not seem to commence his study of chemistry with a concept of potential energy, although later he seemed to incorporate this notion into his concept of force (see appendix 31, §A31.1.2). Kabul recognised only "kinetic" energy in the earth-moon system (K3.B045), that is he did not recognise any potential energy in this situation. Similarly, Kabul thought that the only energy present in the solar system was "kinetic energy" "located on the planets" (K3.B109). However, at one point Kabul appeared to conflate the concepts of the force between two charges and a tacit appreciation of electrical potential energy, when he suggested that the force between two opposite charges would be greater than between two similar charges as "once they've repelled each other, there won't be anything" (K3.B209), whereas as the opposite charges moved together the force "gets bigger" (K3.B219).

Tajinder did recognise potential energy from early in his course, but associated this with one body (e.g. a falling apple) rather than an interactions between bodies. Further the potential energy was not associated with configuration per se: Tajinder only recognised the potential energy when it was converted due to movement (see appendix 31, §A31.1.3).

§10.2: Newtonian mechanics: inertia, equilibrium and reciprocity.

Although Newtonian mechanics is not a requirement of the A level chemistry syllabus, the use of the concepts of force and energy means that the Newtonian framework is implicit. As was discussed in the literature section (§3.1.3), this is an area where it is known that many people, including those who have studied the topic formally, find CURRICULUM SCIENCE counter-intuitive, and where it would seem inappropriate to assume chemistry students share the implicit assumptions underpinning the taught explanatory models of the subject.

In the present research many examples were found of colearners making statements which were inconsistent with these aspects of CURRICULUM SCIENCE. First I will present some examples relating to NEWTON-1 and NEWTON-2 (Newton's first and second laws of motion), which allow us to make the following inferences, amongst others:

- object remaining stationary ⇒ zero resultant force ⇒ forces are balanced
- unbalanced force ⇒ non-zero resultant force ⇒ object not remaining stationary

This chain of inference is important if students are to appreciate how unbalanced forces can bring about changes in configuration at the molecular level during chemical reactions, and why species may be stable. However, colearners in the present study did not always draw these inferences.

§10.2.1: Applications of an impetus notion.

Although the research interviews were largely spent discussing focal figures intended to elicit students' ideas about bonding, some of the colearners spent time discussing some focal figures concerned with force and motion (reproduced in appendix 13). Kabul and Tajinder both demonstrated that they held the type of impetus notions commonly reported in the literature (§3.1.3).

Kabul (see appendix 31, §A31.2.1) thought that an object subject to an applied force would not continue to accelerate, but that the speed "will *settle out on a particular value*, if it's a constant force". Kabul knew an apple would fall down due to the force of gravity. Even when there was no other force acting on the apple he thought it would fall at constant velocity: again he did not expect acceleration.

When asked about an object thrown by hand Kabul thought that it would also be subject to a force from the hand until it reached its highest point, but as it fell back down it would have *used up all its force* - or at least would not have enough left to overcome gravity. Kabul believed "the resultant force is zero" where the object "may just stop ... for an instant, when it has reached its maximum height". When it reached the ground the object was stationary, and therefore Kabul did not think any forces were acting. On the ground gravity was negligible.

When Tajinder was asked to consider the same situation of a ball being thrown in the air, he also demonstrated an impetus conception (see appendix 31, §A31.2.2). So according to Tajinder on the way up "the force of which it was thrown in the air is stronger than the force of gravity". Tajinder saw the apogee as a point where force, rather than momentum, is momentarily zero, so "the force that it gained from being thrown up in the air, is like erm cancelled out by the force of gravity".

Neither Kabul nor Tajinder studied A level physics, and both held impetus notions that were counter to the tacit Newtonian framework underlying chemistry, and which - had they not been colearners in this study - could well have gone undiagnosed and remained unchallenged during their course.

§10.3: Equilibrium.

Chemical structures, such as atoms, molecules and lattices, are understood to be stable as a result of the equilibrium of forces acting on their constituent particles.

Chemical processes may be understood to occur when this equilibrium is disturbed: that is bonds are broken and formed as a consequence of unbalanced forces acting. In organic chemistry the electrostatic nature of such forces is reflected in the terminology: electrophile, nucleophile, electron-rich etc. Again, however, this research suggests that the underlying assumption is not always shared by learners.

§10.3.1: Equilibrium without forces being balanced.

When colearners were shown diagrams of stable systems (objects stationary on the ground, or on a table) they did not always recognise that there was an equilibrium of forces acting. Rather, several of the students took the view that the downward force due to gravity was the larger, or only force acting (see appendix 31, §A31.3.1). Two alternative notions were uncovered. One view was that no upward force was needed, as the object was supported *instead*, or simply that the object could not fall any lower as the ground was in the way. The other view was the downward force had to be greater to hold the object down: if it the forces had been balanced there would have been nothing *stopping* the object from floating away.

Colearners' failure to apply the curriculum science notions of equilibrium were also elicited in systems more central to the present thesis, that is chemical systems.

Application to the atomic nucleus. In Carol's third interview she suggested that the attraction holding the nucleus together had to be *greater* than any repulsions "otherwise it wouldn't be there. It wouldn't exist" (C3.71). In a similar vein, in Edward's first interview he explained that from an electrostatic perspective "the protons repel each other ... in the nucleus" but he was able to explain the nuclear stability as "the force of repulsion, is *less than* the, gluing action of the neutrons" (E1.142), which suggested a non-equilibrium configuration.

Application to atomic structure. In Jagdish's third interview she was able to describe the interactions within an atom in terms of electrostatic charges. However, Jagdish thought that "*the attractions are more stronger* [sic] *than the repulsions*, and that's what's holding it together" (J3.A293). Later in the interview she reiterated that "the attractions from the nucleus, pulling in the electrons" were stronger than the repulsions (J3.A460). However the electrons did not fall into the nucleus as although "they're being attracted, ... the attraction isn't ... that strong" (J3.A463). Later she reiterates again that inside the atom "the attractions" are strongest (J3.A506).

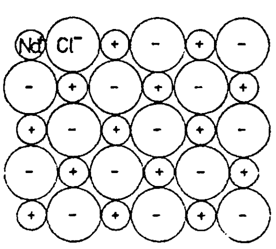
Application to molecules. In the research it was found that a number of colearners thought that in a stable molecule the attractive forces must be larger than the repulsive forces (see appendix 31, §A31.3.2). One rationale for this (Edward, Lovesh) was that if the forces holding the molecule together were not stronger, then it would not be held together - a similar argument to that used in the case of objects on the ground (above). Other colearners (Jagdish, Kabul, Quorat) argued from an analysis of the components of the molecule that there would be more attraction than repulsion - although as such an analysis should not support the premise, this would seem to be a rationalisation of the students' beliefs.

Umar suggested that there was not a balance of forces, although in this case he did not suggest that the electrostatic repulsion was overcome by a larger attraction, but apparently by the effect of the FULL SHELLS EXPLANATORY PRINCIPLE (which is discussed in chapter 11, §11.2), so that "there's repulsion between the two nuclei but the tendency of each of the nuclei to gain an electron to fill its outer shell *is greater* than the repulsion between the nuclei" (U4.A553).

Application to molecular shape. In the second term of her second year Jagdish was recorded (on audio tape) on two occasions discussing some examination questions with another colearner. One of the questions she was asked to discuss with Tajinder was about the shapes of molecules, and Jagdish started off by stating that "lone-pair - lone-pair repulsion is *greater than* lone-pair - bond-pair which is *greater than* bond-pair - bond-pair" (JT1.A079), whereas the actual molecular shape occurs when there is an equilibrium of forces (it is the angles for which 'lone-pair - lone-pair is greater than lone-pair - bond-pair which is greater than bond-pair - bond-pair'). The following day, in discussing another question about shapes of molecules with another colearner (Noor), Jagdish answers her own rhetorical question in the same terms, "okay what's the valence shell electron pair repulsion theory? Lone-pair - lone-pair repulsion is stronger than lone-pair - bond-pair, stronger than bond-pair - bond-pair" (JN1.A317).

In his end-of-first-year examination Kabul used the valence shell electron pair repulsion theory to explain the shapes of a number of molecules. However when discussing the case of ammonia he wrote that "as the repulsion betwn [between] Lone Pair : Bonding Pair > Bonding Pair : Bonding Pair a pyramidal structure is favoured" (A1 examination response, June 1993), i.e. the same mistake that Jagdish had made.

Application to ionic lattices. Carol explained, in her third interview, that whilst there were repulsions "between like charges" (C3.674) in sodium chloride, the structure does not fall apart because they have "gotta be *less*" (C3.676) than the attractions.



focal figure 5

Similarly, Jagdish thought that in the structure,

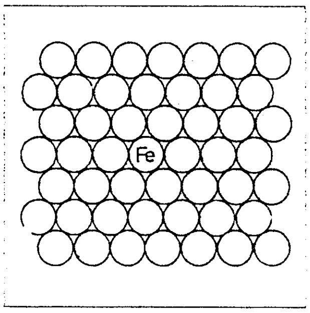
> "there are repulsions, but they're *not as great as the attractions*, ... there are some repulsions between the negative and this negative, that's why you ... have alternate layers ... [so that] they're not close enough to erm actually repel each other a great amount, so ... to split the molecule [sic]."
> J3.B263.

For Jagdish the ions are "just stable in that configuration", in which "the attractions are stronger" (J3.B263).

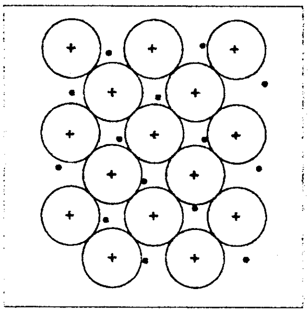
In his first interview Kabul accepted that there was an "attraction force" (K1.A295) between two ions that were bonded, but he did not think there was any force between ions of similar charge (K1.A344). So at the start of the course Kabul's scheme included attractions, but apparently not repulsions. Later in the fourth interview Kabul was discussing focal figure 5, where he recognised there *would* be attractions and repulsions, but he thought "the forces of attraction is [sic] greater" (K4.A535).

In Umar's final interview, near the end of his A level course, he suggested that in sodium chloride (focal figure 5) the forces were not balanced, as "there are attractions between the sodium ions and the chloride ions, and, *these attractions are more than the repulsions* between the individual chloride ions and the sodium plus ions" (U4.A549).

Application to metallic structures. As I have just reported, when Kabul was discussing focal figure 5, he thought that "the forces of attraction is [sic] greater". However in response to questioning he changed this position, to accept that the forces had "balanced out themselves". However, Kabul did not transfer this argument to the metallic case, so when he was then asked about focal figure 6, Kabul suggested "the attraction is greater" than the repulsions (see appendix 31, §A31.3.3).



focal figure 6



focal figure 80

When Tajinder was shown focal figure 80 (meant to represent a metallic structure) his immediate analysis was that "the attractions *seem* [sic] to be stronger" (T1.B357).

Application to a simple molecular solid. In his third interview Tajinder seemed to suggest that, in a similar way, the van der Waals interactions in solid neon led to a non-equilibrium situation,

> "when you have the neon nucleus it's attracting ... all its electron towards it, but then once you get another neon atom it will attract the electrons from the other neon atom, and ... I think the attraction of the nucleus is greater than the repulsion of the electrons."
> T3.A557

Again Tajinder failed to appreciate the balance of forces in a stable structure.

§10.3.2: Equilibrium due to forces acting on different bodies.

Another type of error that some colearners made during the study was to consider an equilibrium of forces possible when two forces *acting on different bodies* were equal.

So Quorat thought that the force on the earth from a falling apple could ***not*** be equal to the force *acting on the earth* else the "*apple* would stay where it was" (see appendix 31, §A31.3.4), whilst Tajinder suggested that the force upwards on the earth had to equal "the force of gravity" or else *the earth* would collapse (see appendix 31, §A31.3.5). In these two cases the colearners came to opposite conclusions by considering the effect of an equilibrium of forces (the force acting on the apple, the force acting on the earth) *as if* both forces acted on a single body.

Tajinder's alternative application of equilibrium was also seen in a number of other contexts (see appendix 31, §A31.3.6). So he considered the earth moon system to be stable because the earth was attracting the moon, which was balanced by the moon *repelling* the earth. He thought that if the moon had been larger than the earth then it would have repelled the earth away to a more distant equilibrium position. When considering a planet orbiting a star Tajinder thought there would be a balance between an attraction *on the planet from the sun*, and a repulsion *from the planets to the sun*. It is not possible to know the extent to which Tajinder's answers were based on long-held views about celestial mechanics rather than the ad hoc creation of an explanatory scheme constructed in the interview context. However, in either case, Tajinder did not seem to realise that his answers contravened fundamental principles of CURRICULUM SCIENCE.

§10.4: Reciprocity of force.

In this section learners' alternative notions to NEWTON-3 are considered. In the research it was found that forces were seen to act from one charged particle onto another, without the reciprocity (as required by NEWTON-3). The 'reaction' forces might be absent, considered as negligible, of the wrong sign (i.e. an attraction paired with a repulsion), or wrong magnitude (i.e. the greatest force acting on the smaller particle).

§10.4.1: Designated forces.

The term *designated forces*, from the work of Watts reported in chapter 3 (§3.1.3), is used where forces are associated with one body, rather than seen as an interaction between bodies. In this research it was found that learners often referred to forces as though they were a property of one body. This was considered to be significant because it is a perspective which logically allows the learner to make NEWTON-3 ERRORS, and to assume that a particular charge gives rise to a certain amount of force (alternative notions discussed below, §10.2.5, §10.3.)

For example Annie interpreted diagrams meant to represent the electron density distributions in bonds as force fields. She appeared to have a notion similar to the CURRICULUM SCIENCE concept of *electric field strength*, but not distinguished from force, so that "the force" or "the pull" from one atomic nucleus might not reach the adjacent atoms. She referred to the "electrostatic *forces coming out from* the ... nucleus of the atom, which pulls the electrons in" (A3.6). For Annie this force originated "*from the nucleus*, ... protons in the nucleus, make up a plus charge, which would draw the electrons in, by ... electrostatic forces" (A3.8). Even at the end of her course she referred to how the nucleus would "*contain the force* ... to pull the electrons towards it" (see appendix 31, §A31.4.1).

In Carol's first interview she referred to how an "aluminium [ion] has *got more of an attractive force*" than a potassium ion (C1.445), as though the force was associated with one species, rather than being an interaction. In the second interview she referred to the lithium iodide bond being polar because "one of them has *got more ... attractive force*, over the other one" (C2.277), in contravention to NEWTON-3, as she was designating forces to single bodies, rather than to the interacting system.

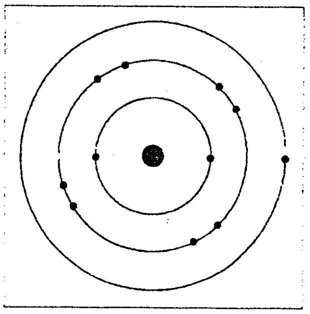
Tajinder referred to a single *central attraction* from the nucleus of an atom to the electrons. When Tajinder was asked about the repulsions in the system he did not construe force to be an interaction between two bodies, asking if he should count the repulsion between two electrons twice - once in each direction. He suggested ionisation energy was "to do with ... *how much force the atom has* at attracting that electron". This is another example of a force being designated to one part of an interacting system (see appendix 31, §A31.4.2).

§10.4.2: The paired force is absent.

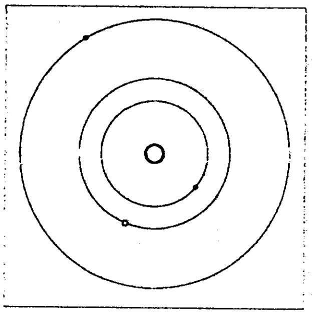
During the study a number of examples of learners not recognising the presence of a 'reaction force' were elicited. Some of these examples originated in the context of macroscopic situations, and some in the context of atomic and molecular interactions.

When asked about an apple falling to the ground both Kabul and Noor thought there would be no force acting on the earth (see appendix 31, §A31.4.3). Noor thought that gravity only acted on the smaller body, so "the apple gets pulled by the earth, because it's, it's, *it's of a greater mass, it's larger in size* than the apple is".

Kabul did not recognise an attractive force acting on the earth in the cases of objects resting on the ground. When a 'massive object' rested on a table Kabul identified a downward force on the table from the object, but not the 'reaction' force (see appendix 31, §A31.4.4).



focal figure 1



focal figure 63

When in her last interview Annie suggested that a nucleus would attract an electron more than vice versa (see below), by way of an analogy the - presumed more familiar - Earth-Sun system was introduced into the discussion. However it transpired that Annie was "not really very up on astronomy" (A4.255). Annie "suppose[d] there must be" (A4.261) a force from the Sun to the Earth, although she had "never really thought about it" (A4.263), and did "not really" (A4.267) think that the Earth attracts the sun, "due to size" because "if you look at the size of the earth compared to the sun, it's such a dot, *there's not really any way that the earth's going to attract, the sun*" (A4.267).

Similarly, when Kabul considered focal figure 63 which represented a simple solar system, he thought there would be a force acting, that "just attracts the planets towards the sun" (K3.B066), but the sun would not experience any force (K3.B071), another example of his failure to apply NEWTON-3. When discussing focal figure 1 in the fourth interview, near the end of the first year of the course, Kabul agreed that there was a force on the outermost electron due to the charge on the nucleus (K4.A132), but he did not think there was any force on the nucleus, due to the electron (K4.A143). Kabul agreed this was a one-way process, (K4.A143), yet another example of what I am labelling a NEWTON-3 ERROR.

Kabul was asked about the case of the hydrogen atom (where the electron and nucleus have charge of equal magnitude), where he suggested that there was a force acting on the electron, and "*theoretically* there should be" a force acting on the nucleus, but he did not think there was (K4.A202). This was followed by laughter from Kabul, and after a pause - while Kabul thinks about the problem for about seventeen seconds - he accepts "all right there will be, there will be a force on nucleus also" (K4.A202), and "in that case it would be equal" (K4.A210). Presumably Kabul had metacognitive awareness that he could not justify his belief, that his 'intuition' and 'learning' were in contradiction.

In Lovesh's third interview, near the end of his first year, he was asked about the forces between the constituent particles in an atom. The extract below shows how he was immediately able to discuss the force acting on an electron, but is nonplused by a question about the force acting on the nucleus.

Although Lovesh eventually decides the nucleus is attracted to the electrons, it is as if the question about the force acting *on the nucleus* is totally incomprehensible - perhaps something Lovesh has never considered. Indeed the question is asked four times before Lovesh offers an opinion. Apparently, reciprocity of forces is not an intuitive notion for this colearner.

I: Do you think there's any force on that electron holding it in that position, keeping it in the atom?
L: Yes, the nucleus attracts all the electrons as well as [i.e. not just] the one, the valence electron.
I: I see. So is there an equal force on all the electrons?
L: No. The valence electron, there is less force because the distance between the nucleus and the electron is greater than the other shells.
• •
I: Right, is there any force on the nucleus there, do you think?
• • • • • [pause, c.5s]
L: What do you mean?
I: Well, this electron apparently experiences a force from the nucleus,
L: Yeah.
I: is there any force on the nucleus, does it experience [sic] any force, or any forces?
• • • • [pause, c.4s]
L: Erm.
• • • [pause, c.3s]
L: Don't know.
I: For example, er, does this electron attract the nucleus, as well as being attracted by it?
• • • • • • • • [pause, c.8s]
L: I don't understand what you mean {laugh}.]
I: Okay. Is this is this electron attracted by the nucleus?
L: Yeah.
I: Is this electron attracted by the nucleus?
L: Yeah.
I: Is this nucleus attracted by this outer electron?
• • • • • • • [pause, c.7s]
L: I think so, yeah.
I: What about by this inner electron, is it attracted by that one?
• • • • [pause, c.4s]
L: Yeah it's, I think it's attracted by all of them.
L3.A189

Quorat was another colearner who knew electrons were attracted towards the nucleus, but did not think this was reciprocated. In Quorat's first interview for the research she discussed the hydrogen molecule (focal figure 2), and initially did not think there was any force acting on the nuclei,

I: Is there any force on the nuclei?
Q: It's positive. But there's no, no outer force acting on it.
I: No outer force?
Q: No.
I: So the only force, ... in that diagram, the force from the nuclei to the electrons?
Q: Well yeah, there's, it's just a positive nucleus that, that's attracting the electrons.
I: So both those electrons are attracted by both positive nuclei?
Q: Yeah.
I: Yeah?
Q: Mm.
I: But there's no force on the nuclei?
Q: No.
I: The force is acting on the electrons?
Q: Uh hm.
I: So, the electrons don't put [sic] a force on the nucleus, it works the other way round?
Q: Yeah.
Q1.A159

So Quorat did not think the force was a reciprocal interaction. Yet, when she started to think about *why* the molecule ***did not fall apart***, she changed her mind,

> "The electrons are pushed apart, but because that electron, this electron is attracted to that [nucleus], and that one to that, like they're both attracted, both the electrons are attracted to both the nucleuses [sic], so therefore they are kept together. ... That means that, *really there is a force of the electrons* that is keep¬ *that is acting on the nucleus*."
> Q1.A177

However, when a little later in the interview Quorat considered focal figure 1 she she thought that in the sodium atom, all the electrons were attracted to the nucleus (Q1.A230), but this was *not* reciprocated,

> I: So all of those are attracted to the nucleus.
> Q: Uh hm.
> I: Is the nucleus attracted to anything?
> Q: No.
> ...
> I: ... there's no force on the nucleus itself?
> Q: No.
> Q1.A230

Two other examples that were elicited were where Annie suggested that in lithium iodide the iodine was pulling the lithium more than vice versa (see appendix 31, §A31.4.5), and when - at the end of his course - Kabul described hydrogen bonding in hydrogen fluoride as a *one way* action of the fluorine on one molecule attracting the hydrogen on another, as the charge on the hydrogen was "too small to attract" the seven valence electrons of the fluorine (see appendix 31, §A31.4.6).

§10.4.3: The paired force has the wrong direction.

In Tajinder's second interview he described how in the earth-moon system there would be "a gravitational force from the earth which is pulling the moon, towards it, ... and there's *also a force from the moon which is repelling the earth away from itself*" (T2.B344). Similarly in a solar system he thought that the sun would attract the planets, but was being *repelled* by them (see appendix 31, §A31.4.7). It seems clear that for Tajinder, at this point in his course, the 'reaction' to an attraction could be a repulsion.

This type of 'error' was also found in the interviews with other colearners. In Annie's first interview she was asked if she knew how the protons and neutrons in the nucleus were held together. She suggested that "forces from the outer ring" (A1.27) were "pushing them" (A1.29). In her second interview Annie suggested there could be some kind of symmetry: "something to do with, 'cause the nucleus pulls in the electrons, so [I don't know] if the electron forces actually help bind the nucleus, in any way" (A2.8). Annie's comments here were tentative, as she was quite clear that she did not know what held the nucleus together, but her suggestion would have required an attraction (on electrons from the nucleus) to have been paired by a repulsion (on the nucleus from the electrons.) At the end of the third interview Annie was asked if the atomic nucleus was attracted by the atomic electrons. Annie thought "no, but, saying that I'll probably go home and somebody's probably discovered that it is" and went on to report that "*obviously* the electrons ... may sort of control what's actually happening in the nucleus. Sort of ... holding the neutrons and the protons together" (A3.491). Although Annie's comments were tentative, her idea recurred at three stages of her course, and it demonstrated that she did not see a difficulty in this type of violation of NEWTON-3.

Carol also attempted to use electrostatic interactions to explain nuclear binding, in her second interview. She knew some explanation was needed as "you would think that a nucleus wouldn't, wouldn't be there really because, it's all protons and they [should] repel, 'cause they're the same charge" (C2.33). Carol thought the protons would repel "but, there's another force, ***might be to do with electrons around the outside that holds it together ... acting from outside***" (C2.40-4).

In appendix 3 there is a description of a questionnaire which was written to diagnose some of the aspects of learners' explanation elicited in this study: THE TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT. This questionnaire was presented to over one hundred A level chemistry students who had studied the topic of ionisation energies. The students were shown focal figure 1, and asked to suggest whether various statements relating to the figure were true or false (see the appendix for details). It was found that 60% of respondents agreed that "***electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons***", a statement which not only has an attraction paired with a repulsion, but also suggests an equilibrium due to forces acting on different bodies (as discussed above, §10.3.2). If the findings from this small scale and unrepresentative survey may be taken as indicative, then it would seem that the beliefs of the colearners in the interview study about the relative directions of 'action-reaction' forces may be shared by a significant proportion of A level chemistry students.

§10.4.4: The paired force has the wrong magnitude.

In §10.4.2, above, several examples were presented where colearners suggested that a larger body will exert a force on smaller body, but not vice versa. There were also many examples in the research of colearners acknowledging the reciprocal nature of forces between bodies, but believing that the larger body exerted the larger force.

So in Tajinder's second interview he recognised that in the context of a falling apple there would be a gravitational force pulling the apple downwards, and an upwards force on the Earth. However, Tajinder thought that "the force pulling the apple downwards" was the larger force (T2.B110).

Similarly Quorat thought that the Earth exerted a larger force on objects than they would exert on it. Quorat justified her belief that the force on the smaller object is greater by, in the case of a falling object, the fact that the object falls and does not stay still; and conversely in the case of an object on the ground, that the object stays still and does not float away (see appendix 31, §A31.4.8).

Quorat applied similar ideas to astronomical systems so the Earth exerted more force on the moon (than vice versa), and the sun exerted more force on the planets (than vice versa) (see appendix 31, §A31.4.9).

Tajinder also thought that the relative sizes of the two forces were related to the relative sizes of the earth and moon, so in his scheme, as long as the earth was larger than the moon "the earth would still have the gravity, and it would pull, the moon towards it", whereas if the moon were bigger then "the force of the moon repelling the earth would be larger than the attraction", and if the earth and the moon were the same size "the forces between the two would be equal" (T2.B374).

Both Tajinder and Quorat applied similar ideas in the context of electrostatic forces, and thought that the force between two electrically charged bodies would be greater on the body with the smaller charge (see appendix 31, §A31.4.10). When colearners were asked about atomic systems it was common to find the suggestions that although the nucleus experienced a force due to an electron, this was *much less* than the force experienced by the electron due to the nucleus (see appendix 31, §A31.4.11). So Quorat reports "the force due to the nucleus on the electrons is greater", and Kabul went further, suggesting that "*even if there is some force* [on the nucleus] it's just negligible". The rationale behind this view seemed to be that a nucleus was larger than an electron, either in terms of mass ("the nucleus is a larger mass than the electron", Noor; electrostatic force on the nucleus is "negligible, because the electron has such a small mass", whereas "the pull is greater towards the nucleus because it's so much bigger", Jagdish), or in terms of the charge ("the nucleus is attracting the electron, *more* than the electron is attracting the nucleus, because the nucleus will have a greater charge", Paminder). The literature reviewed in chapter 3 (§3.1.3) suggests that the apparent distinction may not be too significant as learners commonly fail to clearly distinguish between the basic categories of physics. The importance assigned to the magnitude was made explicit by Kabul who claimed that "a small charge of minus one ... can't attract ... plus eleven, as plus eleven can attract minus one".

In two cases the general 'rule' that the nucleus attracted the electrons more was carried over to the case where there was equal charge on the positive nucleus and negative electron (i.e. the hydrogen atom). In Annie's final interview she suggested that the force on the nucleus would be less than the force on the electrons, and extended this to the case of hydrogen, where "although they they're of similar charge, it seems to be *convention* that that's the way that ... the force goes" (A4.245). Annie also demonstrated that she thought the larger component of a system would exert more force in the context of lithium iodide and potassium fluoride (see appendix 31, §A31.4.12).

In the other case Quorat thought that "the force on the negative" would be a larger, although she could not give any reason, and admitted that she was not sure. (Q2.B439).

In her third interview near the end of the academic year Quorat made a similar comment about the hydrogen *molecule* (focal figure 2) where she thought that "the electrons will probably tend to pull the nucleus towards themselves, but because the nucleus is much bigger, it can pull the electron towards itself" (Q3.A151). When questioned, Quorat accepted that, *in this particular case*, the force on the electron from a nucleus, and the force on the nucleus from the electron were "about the same", but *in general* she thought that "it depends on ... what charge the nucleus has, ... if the overall core charge of the nucleus is greater, then *it will have* a greater force" (Q3.A151).

Quorat's language implies *designated forces* (as discussed above, §10.4.1). Such a belief appears to imply that the charged particles will experience a different size force, as the force is not seen as arising from the mutual interaction, but is associated with one charge as agent, and another as subject,

I: So if you had an atom where the core charge was, let's say, plus seven,
Q: Mm.
I: and there was an electron in the outer shell being attracted to that core,
Q: Yeah.
I: is the core also being attracted to the electron?
Q: Yeah.
I: Which is stronger?
Q: The attraction of the electron towards the nucleus.
I: Is that a greater force?
Q: Yeah.
Q3.A151

In appendix 3 there is a description of a questionnaire which was written to diagnose some of the aspects of learners' explanation elicited in this study: THE TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT. This questionnaire was presented to over one hundred A level chemistry students who had studied the topic of ionisation energies. The students were shown focal figure 1, and asked to suggest whether various statements relating to the figure were true or false (see the appendix for details).

53% of the respondents made the NEWTON-3 ERROR of agreeing with the statement "*the force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron*", and 41% agreed that "*the force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron*". 35% of the respondents thought the statement "*the force on an innermost electron from the nucleus is equal to the force on the nucleus from an innermost electron*" was false. If the findings from this small scale and unrepresentative survey may be taken as indicative, then it would seem that the beliefs of the colearners in the interview study about the relative sizes of 'action-reaction' forces in the atom may be shared by a significant proportion of A level chemistry students.

§10.5: The notion of 'conservation of force'.

I: Right, so what are you saying about the amount of force that the nucleus can give out?
T: It's, it's erm, spread over the number of electron there are. That's what I'm saying.
...
I: So if you've got an extra electron, the nucleus can't just give out extra force?
T: Not if the charge hasn't gone up by one.
I: Right, so a certain charge on the nucleus, implies there's a certain amount of force available,
T: Yeah.
I: And if you increase the number of electrons, you therefore ... decrease the amount of force each one gets?
T: Erm, yeah.
I: Kind of 'conservation of force principle'
T: Yeah.
T7.A559

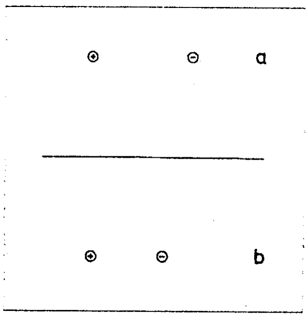
In this study it was found that nuclei were often considered to give rise to a fixed amount of attraction - depending upon charge - which would be shared amongst the electrons available to receive it. In the segment of transcript quoted in the motto above I suggested to colearner Tajinder that he was using a 'conservation of force principle' and he concurred. I have retained this term.

§10.5.1: The conservation of force explanatory principle.

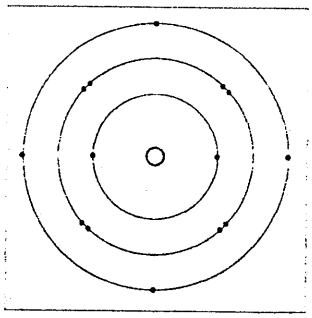
The notion of *conservation of force* was commonly used as an explanatory principle by the colearners in the research. The idea of the nuclear force being *used up* arose in the final interview with Annie, where her understanding of the *shielding* concept was being probed. Rather than explaining the effect of core electrons as being to repel the valence electrons, and thus partly counter the effect of the nuclear force, Annie thought,

> "they'll cut down the amount that it's being pulled towards the nucleus because it's being sort of, *they're being pulled in before*. So, the actual pull on the outer electron will be less than what's in between"
> A4.511

Annie agreed with my interpretation of her comments, that the nucleus has a certain *pulling power*, and that because it's using some of that up, pulling in the core electrons, by the time it gets to the valence shell, it hasn't got much left (A4.516).



focal figure 68

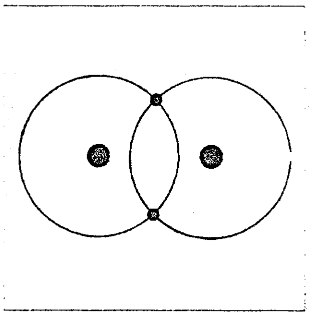


focal figure 75

Tajinder appeared to hold similar notions. In his second interview, he considered focal figure 68, and recognised that there would be a stronger force of attraction in focal figure 68 part (b), than in part (a), because the distance between the positive and negative particles is smaller (T2.B515). However, when he was subsequently shown focal figure 75 he thought that all the electrons would be attracted *equally* (T2.C056). It would seem that Tajinder's recognition that charge separation is important was not elicited in the more complex atom-like structure where the nucleus was attracting many electrons. (The difference could be related to a number of factors: the larger number of charged particles, the atom-like configuration, or the identification of the constituents as electrons and a nucleus rather than abstract charged particles.)

In his fourth interview Tajinder compared the metallic bonding in lithium and sodium. His explanation of the difference in melting temperatures included a reference to the shielding electrons in sodium *containing* the force, that in sodium "there's more surrounding electrons to like *contain the force* because they [nuclei] attract them electrons." Tajinder though that in sodium "those ten electrons ... sort of *block out* ... like *equal out* the core charge" (T4.A289). It would appear that in an atom-like system the nucleus is assumed to have some sort of inherent attracting power, which may be considered to be used-up electron by electron.

In Mike's first interview he made a fairly explicit statement of the CONSERVATION OF FORCE EXPLANATORY PRINCIPAL. He explained that he thought that the size of the nucleus-electron attraction depended upon, "whether there was enough electrons to *fulfil the attraction* of the positive. ... *a single proton attracts a single electron, a one-on-one basis*, ... when you've got two electrons to one proton, they're both attracted, but not as much" (M1.A257).



focal figure 2

In Kabul's fourth interview he also gave an explicit example of the application of the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE He was discussing focal figure 2, where both electrons were being attracted to both nuclei. He thought that in the molecule the force on an electron due to one nucleus, when compared to the force it would have experienced in a single hydrogen atom, was less: "it will experience less force now, because the nucleus [is] attracted to a cloud of two electrons, so the force, you know, *divides*" (K4.A283). So Kabul thought there was "less force going towards that electron" although the *total force* due to the nucleus was "the same". There was the same amount of force as before, but in the molecule it was shared amongst two electrons (K4.A293).

Umar applied a similar logic to considering the force acting in a hydrogen molecule. He thought that in a single hydrogen atom there would be a force between the nucleus and electron, and "it will be an attraction, of plus one" (U3.B341). When he compared this with the force acting between one nucleus and one electron *in the molecule* he thought there would be less force in the molecule than the atom as "the single one [the atom] would have more effect on the single electron because one plus can be for the one minus electron, but here in this [the molecule], in where it's bonded, like, the nucleus, the same charge, one plus, is acting on two electrons, each of one minus, so it'd be less" (U3.B347). To make sure that I had understood Umar's meaning, I spelt out my interpretation for him,

I: ...if I try and paraphrase what you're telling me, you tell me if I've sort of got this right > or not, >
U: < Mm. <
I: erm, [U]. Erm, in this covalent bond the electrons are being shared, between the two atoms.
U: Yeah.
I: But in a sense also, this nucleus is in a sense being shared by these two electrons.
U: Yeah.
I: And therefore it's got less force available to give either of them in¬ independently,
U: Yeah.
I: even though the total force might still be the same?
U: Yeah.
I: Because it's only got a one plus charge and it has to kind of share that between the two electrons.
U: Yeah.
I: Whereas in a single atom that one-plus charge was all available to one electron.
U: Yeah.
U3.B357

§10.5.2: Applications of the conservation of force explanatory principle to ionic size.

Some of the colearners seemed to apply a similar principle when explaining why cationic radii are smaller than atomic radii. For example, in a test answer Jagdish suggested that "because the core charge of the Al [aluminium ion] has less electrons to pull in, it can pull in more tightly" (assessment response, March 1993). Similarly, in her end-of-first-year-examination, Jagdish explained the greater size of the fluorine anion compared to the atom partly in terms of "more repulsion", but she also suggested "because of the extra electron ... the core charge cannot pull on the electrons as tightly". Lovesh's explanation for why the fluoride ion was larger than the potassium ion was partly in terms of the repulsion between electrons in the fluoride ion, but also in terms of the increased attraction acting on the potassium electrons - that potassium had "lost an electron and so the effective nuclear charge ... attracts the electrons in more closer" (L4.A371).

Both of these examples from colearners are ambiguous, in that they could be read as just clumsy phrasing. However the following two explanations of changes in radius on forming an ion (from incidental data collected from other students) are more explicit in their use of CONSERVATION OF FORCE as an explanatory principle,

> "the radius will become smaller when an electron is taken away from outer shell because the nucleus's attraction will have more effect ie/ it's *force will be distributed* amongst less atoms [sic, electrons]."
> (End-of-first-year examination response, June 1994.)

> "As the ion has an extra electron in its valent shell means the core charge, which remains the same, has to *spread its attractive forces* equally to each electron thus resulting in less attractive forces on each valent electron and larger atomic radius."
> (End-of-first-year examination response, June 1994.)

§10.5.3: Applications of the conservation of force explanatory principle to ionisation energy.

The topic that provided the richest evidence of colearners applying a CONSERVATION OF FORCE EXPLANATORY PRINCIPLE was patterns in ionisation energies (an important part of the study of periodic trends in chemistry). It was in an attempt to understand this topic that Tajinder used his CONSERVATION OF FORCE EXPLANATORY PRINCIPLE when he was discussing atomic energy levels during interviews in his first year (see appendix 31, §A31.5.1). In his sixth interview he considered how the energy levels of electrons in the helium atom, and helium cation might compare. Tajinder thought that the energy level would be different "because in the ion, the two proton's are only attracting one electron, but in [the atom] they're they've got two electrons to attract, so therefore like sort of *their attraction is like spread out over two instead of one*". In the following interview he repeated his idea, that "the protons only have ... one electron to attract, in helium ion, [whereas in] helium atom they've got two electrons to attract". So the force from the nucleus was "spread over the number of electron there are". It was explained to Tajinder that force was not conserved in this way, but that the ionisation energy of the atom would be less due to repulsion between the two electrons. Tajinder accepted this at the time, but later, when the second and third ionisations of lithium were considered, his initial tendency was still to think in terms of force conservation.

Similar reasoning was applied to this topic by other colearners. For example when Rhea attempted to explain the pattern in the successive ionisation energies of magnesium in an assessment, her response included two phrases that seemed to imply she was applying the CONSERVATION OF FORCE principle,

> "Then once that shell [the L shell] has been emptied, again you have to break into another shell, but by this time you have an ion with +10 charge, holding 2 electrons. so the nucleus has the two protons keeping the electron attracted to the nucleus, and also *a spare 10 protons left over* from the 10 electrons removed. to hold the 2 electrons very tightly so as well as having to break in to a new shell of electrons, it has to break into a shell with a *+6 charge for each electron* that is to be removed. so alot [sic] of ionisation energy is required to remove the final two electrons."
> (Response to assessment question, March 1993.)

Rhea seems to have thought that each proton gives rise to a certain amount of force, sufficient to attract one electron under normal conditions. Thus the removal of ten electrons gives an ion which has "10 spare protons", which can be redistributed to give "a +6 charge for each electron".

In response to the same question Jagdish wrote that

> "there is a slight increase in I.E. [ionisation energy] when the second electron is removed because although the core charge doesn't change, *because there is one less electron the positive nuclear charge can pull on the electrons a little more*, slightly decreasing the atomic radius [therefore] more energy is needed to remove it".
> (Response to assessment question, March 1993.)

She also wrote that when electrons were removed from the second shell

> "there is a slight increase in energy needed because again although at the same energy level *the core charge can pull in more tightly each time an electron is removed* and reduce the radius".
> (Response to assessment question, March 1993.)

Jagdish's answers seem to imply that having fewer electrons to attract is itself a cause of greater attraction to the nucleus.

In Tajinder's fifth interview he attempted to explain the difference in first ionisation energies for beryllium and magnesium. His explanation was complex, and included valid electrostatic considerations, but part of his reasoning was that "there's more electrons in the magnesium atom, ... and therefore the core hasn't got as much attraction to the outermost electrons ***because there's more electrons to attract***, and therefore the amount of energy you need is less than beryllium" (T5.A085).

Another suggestion of this notion may be detected in Kabul's discussion with Mike about ionisation energies, when Kabul comments that "as we start removing the electrons, you know the net nuclear charge acting on the remaining electrons will increase" (KM1.29). In his final interview Kabul explained that when the outermost electron was removed from a sodium atom the force acting on the remaining electrons "would be more compared to before" (K6.A132), "because there are eleven protons in the nucleus, you know, holding ten electrons, so there would be more force, but before there were, you know, eleven protons and eleven electrons, so ***the force divides***" (K6.A136).

If a second electron was removed, the force on those remaining increased again (K6.A139), and if all but one electron was removed the force on that one electron would be "much more", indeed Kabul thought it would be "probably more than" twice as much, and perhaps ten, eleven or twelve times as much (K6.A143). He thought he could work out the force on an electron using "Coulomb's law, and ... measure the distance, and ... just bung it in the formula and you know the force" (K6.A153). Kabul thought he could carry out the calculation for the electron when in a sodium atom, and repeat the calculation for the situation when it was the only electron, and he would get a bigger answer (K6.A161). It would appear that even when Kabul had available the appropriate CURRICULUM SCIENCE tools to analyse such a situation, his preexisting intuitions about force and charge took precedence in his thinking.

Lovesh also retained the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE through his course, and in his final interview he suggested that if the outer electron was removed from a sodium atom the other electrons would "be attracted even more" (L4.A130). His reasoning was based on the amount of positive charge in the nucleus compared to the number of electrons being attracted "because now the ... number of electrons is less than the number of protons, so there's overall more positive charge in the middle so that attracts them even more" (L4.A130).

Umar also seemed to apply the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE in his explanations of ionisation energy throughout his course (see appendix 31, §A31.5.2). So Umar's response to an assessment question on ionisation energies shortly after being taught about the topic suggested he also thought in terms of nuclear charge being shared between the electrons. Umar had drawn an appropriate diagram for the successive ionisations of magnesium, but his explanation of this pattern included both points which would be judged valid from a CURRICULUM SCIENCE perspective, and several references to the core charge being shared amongst the electrons present. In all there are four references to the increasing share of core charge that a smaller number of electrons experience (the $3s^1$ electron "*has slightly more nuclear charge action[sic] on it once the $3s^2$ electron has been removed*"; "as once each previous electron is removed *there is greater attraction by the nuclear charge on the remaining electrons, so the same nuclear charge is pulling on less no. of electrons*"; "*there is a greater core charge pulling on less electrons*"; "*once the [$1s^2$ electron has been removed] there is increased core charge attraction to the $1s^1$ electron*").

Near the end of the first year of his course Umar suggested that because an anion had more electrons than protons "each electron's got less charge on it overall from the core charge" (U3.A212). In a neutral atom the "charge on the nucleus to [a specific] electron" would be "plus one", because "effectively it's like one plus to each electron", however if an electron were removed then "the same positive charge is acting on a less number of electrons". In a Na^{9+} ion "there's an eleven plus charge, on two electrons" and so "*effectively five and a half, positive to one minus electron*", and in the Na^{10+} ion "they'd be eleven plus on the one electron" and so a "much stronger force". In the end-of-first-year examination Umar wrote that "once the 1st electron is removed [from a magnesium atom] there is increased pull from the nucleus on the 2nd electron *as it is the only one in that shell*" (A1 examination response, June 1993). Even at the end of his A level course Umar explained increasing successive ionisation energies as due to "the *same nuclear charge pulling on less electrons* so there's a greater electrostatic force ... each time". So when a sodium atom was ionised,

> "they'll be ten electrons and eleven-plus nuclear charge so they'll be attracted more, because the *same positive charge pulling on less electrons*, so, it's *more on each electron* [as] the amount of energy [sic] that that nuclear charge used in pulling that outer electron which is one, po-, one plus, is like *distributed across the other remaining electrons*, that same energy" (U4.A089).

So according to Umar's understanding, when one electron was removed from the sodium atom the nucleus "just attracts [the remaining electrons] more. What it would have used to attract the [eleven] electrons it uses to attract the remaining ten" (U4.A102). If a second electron was removed "then there'll be the same nuclear charge pulling on the remaining nine electrons so it'd be stronger even more" (U4.A110). Each time an electron was removed "there's a stronger nuclear charge on the electrons" (U4.A115), until when only one electron remained "it'd be attracted much more stronger, 'cause there'd be plus-eleven charge pulling on only one electron" (U4.A120).

§10.5.4: The conservation of force explanatory principle as a common notion.

Incidental data collected from other chemistry students includes explanations that are similar to those from the colearners in this study, and suggest that the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE may be more widely applied. The following examples concern the ionisation of magnesium, and are quite explicit in suggesting that the force of the nucleus is shared amongst the electrons present,

> "When an electron is removed the effective core charge is *shared* out between 1 less electron therefore increasing the energy needed to remove another electron."
> (End of first year examination response, June 1994.)

> "The loss of one electron has meant the remaining electrons receive the lost electron[']s *share* of the attraction to the centre so the valence shell is pulled more tightly in to the centre. This requires more energy to free the second electron from the valence shell hence the rise in ionisation energy."
> (End of first year examination response, June 1994.)

> "Once the first electron is removed, the nuclear charge is no longer *shared* amongst two valence electrons, but one. There is a stronger attraction which means more energy is needed to remove it."
> (End of first year examination response, June 1994.)

In appendix 3 there is a description of a questionnaire which was written to diagnose some of the aspects of learners' explanations elicited in this study: THE TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT. This questionnaire was presented to over one hundred A level chemistry students who had studied the topic of ionisation energies. The students were shown focal figure 1 (representing a sodium atom), and asked to suggest whether various statements relating to the figure were true or false (see the appendix for details).

Most of the respondents, 72%, agreed that "*the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons*" was true. Almost as many, 69% of respondents, agreed that "*if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus*", and a similar proportion, 70%, agreed that "*the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus*". An even greater proportion, 79%, agreed that "*after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus*". 74% of respondents agreed with the statement "*the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed*". If the findings from this small scale and unrepresentative survey may be taken as indicative, then it would seem that THE CONSERVATION OF FORCE EXPLANATORY PRINCIPLE may be shared by a significant proportion of A level chemistry students.

The present research may be seen to suggest that learners studying A level chemistry may not only designate forces to specific charged particles, but may see the magnitude of the designated force as being proportional to the particle's charge, and therefore being shared amongst whatever oppositely charged particles are construed as being attracted.

Chapter 11.

Learners' application of 'octet thinking'.

§11.0: The full shells explanatory principle.

In the present research it was found that one of the most significant factors influencing learners' developing understanding of chemical bonding was the presence of complexes of alternative conceptions which were not consistent with CURRICULUM SCIENCE, and which provided learners with alternative rationales for the formation of chemical bonds. These complexes were based around the octet rule heuristic, but developed into a fundamental explanatory principle. Each learner's thinking was to some extent unique, as the case studies of Annie and Tajinder demonstrate (see chapters 7 and 8 respectively). However, as with Annie and Tajinder, all the colearners in the study showed some aspects of what I will loosely term *octet thinking*. In this chapter the main features of *octet thinking* will be described and illustrated. In the final chapter I will suggest that, on the evidence of the present research, the FULL SHELLS EXPLANATORY PRINCIPLE forms the basis of a common alternative conceptual framework applied by learners in chemistry (§12.3). However, I would suggest that the presence in learners' cognitive structures of the set of related alternative conceptions discussed in this chapter has implications for learning about bonding, and other aspects of chemistry (§12.5), regardless of whether the label of alternative framework is considered appropriate.

§11.1: An atomic ontology: atoms as the units of matter - the building block metaphor.

The research suggests that atoms are ascribed a special ontological significance by learners, so that chemical systems tend to be conceptualised in terms of combinations of atoms, although this may not *always* be the most useful and appropriate approach. The notion of electrons *belonging* to atoms (see below, §11.1.4) may be associated with this tendency to perceive discrete neutral atoms as some sort of 'natural' unit of matter. The evidence from the data collected suggests that the metaphor of atoms as *the building blocks of matter* may be adopted by learners, without consideration of the ways in which atoms are *not* analogous to building blocks.

One colearner in the study, Kabul, seemed unable to conceive of the possibility of an ion existing *unless* it had been formed by electron transfer between neutral atoms (see appendix 32, §A32.1.1).

Evidence from tasks set to new A level students as induction exercises demonstrate that Kabul's view was not idiosyncratic. When new students were asked to define the term 'atom' as part of an induction exercise, several suggested that atoms were indivisible or the smallest components in matter (see appendix 32, §A32.1.2). Although these comments reflect the original meaning of *atomos*, they are contrary to a model of chemistry that understands bonding as the electrostatic interactions between sub-atomic units (i.e. cores, electrons). Some students' definitions seemed to reflect this tension between the atom as indivisible, and as a compound entity, referring to the atom as both the 'smallest particle' possible, or the 'simplest structure in chemistry', and then going on to describe its subatomic components (see appendix 32, §A32.1.3).

Some students seem to explicitly use the metaphor of *atom as building block*, so the atom is seen as the "building block of *all substances*" (induction exercise, September 1995), or put even more strongly, the "atom is a particle which is the building block of *everything*" (induction exercise, September 1993).

Seeing an atom as the basic unit means that molecules are seen as combinations of atoms, rather than as basic entities, or as systems of atomic nuclei/cores and electrons (see appendix 32, §A32.1.4, c.f. chapter 12, §12.4.5).

The same phenomena may be found in many students' definitions of ions, that is - as with Kabul - ions are seen as altered atoms. Rather than ions being viewed as entities in their own right, they may be seen as atoms (or molecules, which are derived from atoms) that have had electrons added or removed (see appendix 32, §A32.1.5).

§11.1.1: The assumption of initial atomicity.

This research suggests that in A level chemistry some learners may assume that any chemical system they are asked to consider has evolved from discrete atoms. For learners who assign atoms the ontological status of being the basic units of matter, it is perhaps understandable that this is so: i.e., that they should conceptualise information presented to them, in terms of what they perceive to be the basic level of analysis for the subject.

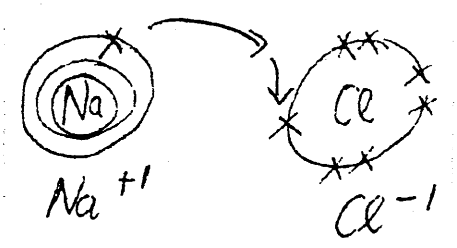
For example, in Tajinder's third interview he apparently brought to mind an isolated atom (that has "four" outer shell electrons) when he was asked about an atom *in a piece of carbon* (see appendix 32, §A32.2.1). A similar example occurred in Kabul's fifth interview when he discussed hybridisation. He talked about diamond as though there were atomic orbitals present, that could be hybridised *when* bonds were to be formed (see appendix 32, §A32.2.2).

In an interview shortly before his A level examinations Kabul explained that sodium would react with hydrogen as the hydrogen *atoms* had "just one electron" and could accommodate another, thus conceptualising hydrogen as if it existing as isolated atoms rather than molecules. It would appear that throughout his A level course, when thinking of such reactions, Kabul assumed the reactants initially existed as atoms. When this was challenged he appeared to have no other rationale for explaining the reaction (see appendix 32, §A32.2.3).

Incidental data collected from induction exercises with A level chemistry classes demonstrate that it is not uncommon for learners to make an assumption that reactions occur between elements which are in the form of discrete atoms (see appendix 32, §A32.2.4).

In the following example, the atomic status of the reactants is emphasised with an illustration,

> "Sodium has to get rid of an electron to achieve a full outer shell status and Chlorine has to *try* to gain an electron to complete its outer shell. Therefore Na and Cl combine in an ionic bond where Na gives Cl an electron to complete both shells and both atoms stay together in an ionic bond because they both [sic] have opposite charges."



(Induction exercise, September 1994.)

The assumption of initial atomicity is not restricted to students *commencing* their A level studies, and the following examples were collected from students who had completed one term of A level study,

> "Sodium atom has one electron more while chlorine atom *needs* one electron to complete an inert electronic configuration. Hence both atoms react with each other ..."

> "Carbon *needs* 4 electrons while oxygen *needs* 2 electrons to complete its outer shell. Hence to gain inert gas configuration, 1 *molecule* of carbon combines with 2 *molecules* of oxygen to form carbon dioxide which has covalent bonding"
>
> (First year coursework exercise, January 1995.)

The potency of *octet thinking* may be seen in the second example above, where the explicit acknowledgement that the reactants are in the form of molecules does *not* prevent the students applying the assumption of reagent atomicity.

Although the assumption of initial atomicity is inappropriate from a CURRICULUM SCIENCE perspective, a perusal of some school text books soon revealed examples of authors' explanations that seemed to support such an interpretation (see appendix 32, §A32.5).

§11.1.2: Atoms as hard sphere.

Atoms are sometimes compared to billiard balls. This is an analogy made in *physics* when the elastic nature of collisions between particles is important for developing the kinetic model of a gas. (Of course if *all* collisions between particles were elastic there would be no chemical reactions.) In *chemistry* it is important for learners to realise that in some situations atomic particles do behave similarly to hard spheres, but in other contexts the mutual penetration of atoms and molecules is very important.

In her third interview Annie was asked why in sodium chloride (focal figure 5) the ions do not move any closer, if they are attracted together. Annie suggests "they could only get so, so close, because of the size of the atoms" (A3.202). This answer implies that atoms have size in the same sense as a billiard ball, whereas an atom is a 'fuzzy' object, where the notion of size is more problematic. Her answer also reflects some of the comments presented in chapter 10, where an object may be perceived to rest on the ground when acted upon by the (unbalanced) force of gravity, because it can not fall any further: in other words support (or in this case integrity) is seen as self evident, and the learners does not need to invoke the action of a force.

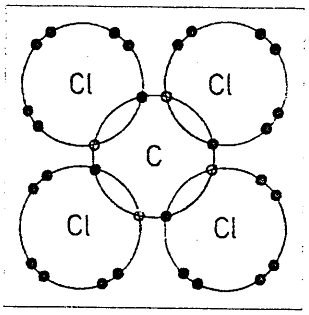
§11.1.3: Isolated electrons.

The high ontological status learners appear to ascribe to atoms may mean that electrons, as parts of atoms, may not be considered to be stable outside the atom. So, in his first interview Tajinder suggested that an electron could not be removed from an atom, unless it could "go to another atom", "because it just can't exist by itself" (T1.A421). Later in the interview Tajinder did change his mind when he thought about a metal as there would be "free electrons roaming around" (T1.B074). However, in the case of a single sodium atom, Tajinder explained that an electron "wouldn't just roam off by itself" (T1.B094). In his second interview Tajinder reiterated that an electron "would be able to move about *in the lump of metal* ... it wouldn't just float off by itself" (T2.A168).

§11.1.4: Ownership of electrons.

It was found in the research that electrons were commonly seen to *belong to* particular atoms. When an isolated atom is considered this notion of 'belonging to' could be equated with 'being part of' an atom. In the case of a molecule those electrons classed as core, or lone-pair ('non-bonding') electrons *might* be considered - from a CURRICULUM SCIENCE perspective - to belong to a particular atom *in a sense that* relates to the extent to which the atomic orbitals are perturbed (i.e. the extent to which the molecular orbitals occupied by the electrons are similar to the atomic orbitals that would be occupied in the absence of the rest of the molecule, see §12.5). However it was found that for learners, the notion of electron ownership was applied to bonding electrons that - from a CURRICULUM SCIENCE perspective - could *not* be said to have a particular association with one specific atomic core in the molecule.

It is conventional in school science and chemistry texts, and to some extent in A level texts, to use variations on 'dot and cross' diagrams, where electrons are shown by different symbols according to which atom that are said to have originated. (This may be useful to pupils to draw attention to the point that the *number* of electrons has not changed during a reaction). Focal figure 3 followed this convention:



focal figure 3

A number of the colearners interviewed interpreted the distinction between the electrons in terms of which atom they 'belonged' to. Further questioning suggested that in *some* cases the word 'belong' was being used casually, but for others the ownership of the electrons was more significant (see appendix 32, §A32.3.1).

Where the term 'belong' is used as no more than a way of indicating which electron originated from where, then it may not be seen as important. However, later in this chapter (§11.4) it will be shown that *although* from a CURRICULUM SCIENCE perspective, there is no significance to an electron's history - the electron has no memory of where it has previously been - for some learners the electron's 'history' *is* seen as having consequences. In Paminder's first interview she suggested that the protons in the chlorine nucleus were only attracted to chlorine electrons, and the protons in the carbon nucleus were only attracted to carbon electrons (see appendix 32, §A32.3.2).

It will be shown below (§11.4.2) that electron history is considered a determinant of *whether ionic bonds exist* between adjacent sodium and chloride ions in a sodium chloride lattice. When Mike discussed sodium chloride in his first interview, he described the conjectured electron transfer event as "the sodium atom is *lending* chlorine one of its electrons" (M1.A375). In Carol's second interview she suggested that electron transfer in sodium chloride was not complete as "the sodium will still want *its* electrons back" (C2.211).

§11.1.5: Covalent bonding as sharing of electrons.

In this research it was found that the covalent bond was often described in terms of atoms *sharing* electrons. This is a term which is often used in books, and therefore has some currency within CURRICULUM SCIENCE. However during an A level course learners are expected to develop more sophisticated models of the bond, and it is therefore of interest if they continue to use this level of description as they undertake their A level studies. This is particularly so if learners *define* the covalent bond as 'sharing electrons' *as though* this is a full and sufficient description.

The significance of the use of this description may be clear from Tajinder's case (chapter 8). By the end of his course Tajinder had three alternative explanatory principles he would use to discuss bonding. To describe a bond as electrons being 'shared' has little relevance to either his COULOMBIC FORCES EXPLANATORY PRINCIPLE, nor his MINIMUM ENERGY EXPLANATORY PRINCIPLE, the bases of the two more sophisticated complexes of ideas he developed through A level study. Rather *sharing* of electrons is a definition of the covalent bond which derives from Tajinder's OCTET RULE EXPLANATORY PRINCIPLE, the deficient basis for explaining bonding that he brought from his school level study.

Indeed this terminology derives from the notion of atoms owning electrons (see above, §11.1.4). The term 'sharing' derives is potentially from a scheme such that *by* sharing electrons, an atom may count both its own electrons, and the electrons *donated* to be *shared* by atoms bonded to it, towards having a full outer shell. It is interesting to note that the term 'sharing' is anthropomorphic - that is, atoms share by analogy with human social behaviour - and in such a scheme the agents bringing about sharing (and therefore bonding) appear to be the atoms themselves. (Later in this chapter more widespread anthropomorphism in discussing bonding will be identified, §11.3.)

Of course, if a learner uses the term 'atoms share electrons' as shorthand for, say, '*a pair of negatively charged electrons are attracted to, and by, a pair of positively charged atomic cores, and the electrostatic forces bind the atoms together*', or alternatively to mean something like, '*a pair of electrons occupy a bonding molecular orbital formed by the overlap of two atomic orbitals that were at higher energy levels, and therefore the energy of the molecular species is lower compared with the atoms*', then the term is not problematic. However in some of the discussions with learners undertaken for this research it was clear that the term 'sharing' was used more literally, and was seen as a sufficient explanation for the covalent bond.

The use of the term 'sharing' was ubiquitous amongst the colearners in this study near the beginning of their A level study (see appendix 32, §A32.4.1), and was also found in data collected from other learners starting out on A level (see appendix 32, §A32.4.2). Most of the colearners continued to talk of 'sharing' even when they had been taught about bonding at A level (see appendix 32, §A32.4.3).

In some cases the definition of the covalent bond as sharing of electrons is probably little more than habit, and does not exclude the presence of alternative models of description (as seen with Tajinder in chapter 8, §8.4.5). However, in at least some cases, *sharing* is seen to be an explanation of the bond in itself. This seemed to be the case in Paminder's first interview where the sharing itself was described as a *link* and "like a force" (see appendix 32, §A32.4.4). Similarly in Umar's first interview he appeared to think that the sharing held atoms together simply because they were combined as *one whole thing* (see appendix 32, §A32.4.5).

For a student who does not share a CURRICULUM SCIENCE typology of forces (c.f. §3.1.3 and chapter 10), such 'sharing' may be seen as the *cause* of a force, rather than as a metaphor for describing a system of interacting electrostatic charges. So one learner setting out on an A level course explained that "when two or more atoms join their electrons are shared (covalent) or given (ionic) this *makes a force* between the atoms" (induction exercise, September 1995).

§11.2: The octet rule as the basis of an explanatory principle.

> "bonding is when 2 atoms chemically combine to become a molecule of sorts. The 2 types of bonding are IONIC (donating electrons) and COVALENT (sharing electrons). It is done in order to try *to achieve a stable structure i.e. 8 electrons in the outer shell* of the atom"
>
> From an A level induction exercise, September 1995

In chapters 7 and 8 it was suggested that Annie and Tajinder's understanding of chemical bonding could be interpreted in terms of key 'explanatory principles' which formed the basis of many of their interview responses. In both cases one explanatory principle was related to the octet rule, and was used throughout the course. The two principles were similar, but to emphasise the unique nature of learners' ideas, they were given distinct labels: the STABLE SHELLS EXPLANATORY PRINCIPLE (Annie), and the OCTET RULE EXPLANATORY PRINCIPLE (Tajinder). In the present chapter it is suggested that this research suggests that *the application of ideas based on the octet rule as the basis for explaining chemical bonding - and related phenomena - is ubiquitous among chemistry learners at this level.*

The case studies in chapters 7 and 8 have demonstrated that although Annie and Tajinder used similar explanatory principles, they developed a different range of explanatory schemes from them, so that the complex of ideas elicited from Annie based on her STABLE SHELLS EXPLANATORY PRINCIPLE, does not match absolutely with the set of ideas elicited from Tajinder based on his OCTET RULE EXPLANATORY PRINCIPLE. In a similar way, the other colearners in the study also used 'octet thinking' to different extents, and in varying ways, and in somewhat different contexts during their interviews. However all of the colearners in the study seemed to hold in their cognitive structures something akin to Annie's STABLE SHELLS EXPLANATORY PRINCIPLE and Tajinder's OCTET RULE EXPLANATORY PRINCIPLE, which will be given the generic label of the FULL SHELLS EXPLANATORY PRINCIPLE.

> The basis of 'octet thinking' is
>
> the FULL SHELLS EXPLANATORY PRINCIPLE:
>
> that atoms form bonds in order to achieve stable electronic configurations
>
> (variously referred to as octets, full outer shells or noble gas configurations/structures).

Each of the colearners may be shown to be applying a variant of this principle at some point during the interviews (see appendix 33, §A33.1.1), so for example Noor explained that bonding "involves obtaining *a full outer shell*", and that "in all cases what an atom is trying to do is to become stable, and so obtain a ***full outer shell***" (N3.A150). Incidental data provides some evidence that other chemistry learners also apply this principle (see appendix 33, §A33.1.2).

Although using the octet rule as an explanatory principle is inappropriate from a CURRICULUM SCIENCE perspective, a perusal of some school text books soon revealed examples of authors' explanations that seemed to support such an interpretation (see appendix 33, §A33.11).

§11.2.1: Explaining the covalent bond.

In terms of the FULL SHELLS EXPLANATORY PRINCIPLE, a covalent bond enables atoms to obtain stable electronic structures by sharing electrons, which are then 'counted' towards both of the sharing atoms.

In the data collected there were many examples of colearners explaining covalent bonds being described in terms of "the sharing of electrons between two species, in order to gain fully full outer shell" (see appendix 33, §A33.2.1).

In terms of the FULL SHELLS EXPLANATORY PRINCIPLE, a double bond is simply the sharing of two pairs of electrons, and in the research there were several examples of the bond in an oxygen molecule being described in these terms (see appendix 33, §A33.2.2).

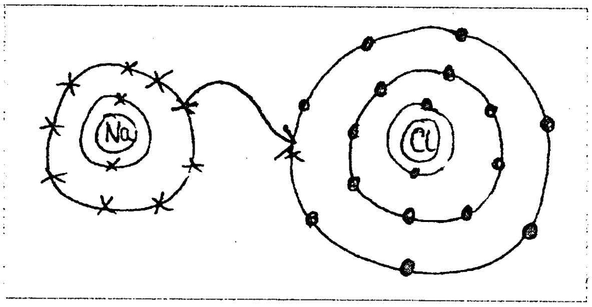
'Incidental data' collected from chemistry students suggests that the notion of the covalent bond as sharing of electrons to give full electron shells is not restricted to the colearners in this study. For example comments reflecting the FULL SHELLS EXPLANATORY PRINCIPLE have been elicited in relation to a number of different molecules in induction exercises by students embarking on A level study (see appendix 33, §A33.2.3). As has been seen with the colearners interviewed for this research, the FULL SHELLS EXPLANATORY PRINCIPLE is retained and applied by chemistry students after they have been taught the more sophisticated models of the A level curriculum (see appendix 33, §A33.2.4).

An interesting variation on the model of covalent bonding discussed here was found in the case of Mike. For most learners applying the FULL SHELLS EXPLANATORY PRINCIPLE, shared electrons are counted fully towards the octets of both sharing atoms. However in his second interview Mike revealed his own interpretation was different, i.e. that a shared electron only counted as half an electron for each atom, so that more electrons would need to be shared to reach the required number (see appendix 33, §A33.2.5).

§11.2.2: Explaining the ionic bond.

In terms of the FULL SHELLS EXPLANATORY PRINCIPLE, ionic bonding occurs when atoms achieve stable electronic configurations through electron transfer. There were many examples of colearners explaining the ionic bond in this way (see appendix 33, §A33.3.1), and these were not limited to students just commencing the A level course. So at the end of her first year Jagdish explained how a sodium atom could "form a more *stable configuration* by giving one of the electrons to the chlorine and forming a bond, and so it would be at lower energy level" (J3.A376); and at the end of her course Annie explained how ionic bonding involved one atom donating electrons, to another which is "sort of deficient in electrons", so that it would have the "number it needs, to like have a *full stable outer shell* which is *what all sort of compounds are aiming for*" (A4.14).

The notion of the ionic bond being an electron transfer to give full shells is reflected in evidence collected from other chemistry learners, such as the following datum presented in an induction exercise,



"Sodium loses one electron *to complete the outer shell* for chlorine."

(From an induction exercise, September 1995.)

and the following definition, taken from a revision exercise at the end of one year of study,

> Ionic bonding is the exchange of electrons in two or more atoms to achieve the result of a *full vaient shell.*
> (concept map on chemical bonding, June 1994.)

§11.2.3: Explaining the metallic bond.

The metallic bond cannot be explained in terms of the FULL SHELLS EXPLANATORY PRINCIPLE as readily as the covalent and ionic cases, as in a metal the mean number of valent electrons per atom is unchanged from the isolated atom. (It is suggested later in the chapter that this may explain why pure metals are sometimes considered not to involve chemical bonds, or at least not 'proper' bonds, see §11.7.2.) However, some colearners in the study *were* able to construe the metallic bond in terms consistent with the FULL SHELLS EXPLANATORY PRINCIPLE. So electrons were conceptualised as being shared, *or* being moved around so that the atoms took turns in having full shells (either by gaining enough, *or* losing enough), or the electrons were considered to have been donated to the lattice and so they were no longer on the atoms (see appendix 33, §A33.4.1).

§11.2.4: Explaining the dative bond.

Colearners in this study also used the FULL SHELLS EXPLANATORY PRINCIPLE to explain dative bonds. So Kabul explained that aluminium chloride dimerised as "in order to attain a stable state you must have eight electrons" (K4.B414). Similar explanations were given by several other colearners (see appendix 33, §A33.5.1).

§11.2.5: Rationale for chemical reactions.

Chemical reactions may be described at the molecular scale in terms of bond breaking and bond making: bond fission and bond formation. The FULL SHELLS EXPLANATORY PRINCIPLE may therefore be used to explain chemical reactions, as well as bonds in themselves.

At the end of her course Debra explained the monatomic nature of noble gas molecules in terms of the atoms already having full shells (D3.37) and a similar argument was put by Lovesh in his second interview (see appendix 33, §A33.6.1). Similarly, at the end of Kabul's course he attempted to explain the reaction between sodium and hydrogen in terms of the hydrogen *atoms* being able to accommodate another electron (see appendix 33, §A33.6.2).

§11.2.6: Octets, *or* full shells, *or* noble gas electronic configurations?

It was suggested above (§11.2) that when learners apply the FULL SHELLS EXPLANATORY PRINCIPLE some refer to octets, others to full shells, and yet others to noble (or inert) gas structures, and this is illustrated by the various examples given in appendix 33, §A33.7). These terms seem to often be used as if synonymous. However according to CURRICULUM SCIENCE only two of the noble gas structures have full outer shells (as the first four shells would be full with 2, 8, 18 and 32 electrons respectively), and helium does not have an octet.

Some colearners demonstrated confusion over this aspect of atomic structure. So although Edward was able to report that the maximum number of electrons in a shell was given by the formula $2n^2$, on another occasion he stated that the third atomic shell could only contain four orbitals, i.e. a maximum of eight electrons (see appendix 33, §A33.7.1).

Jagdish and Paminder also thought that the third shell could only hold a maximum of eight electrons (see appendix 33, §A33.7.2).

Although from a CURRICULUM SCIENCE perspective the terms *octets*, *full shells*, and *noble* (or *inert*) *gas electronic configurations* are *not* synonymous, several school science texts perused during this research presented statements which - like some of my colearners - clearly used incorrect terminology (see appendix 33, §A33.12).

§11.2.7: Bond polarity and electronegativity.

Bond polarity is an important concept in A level chemistry, but one which is not explained by the FULL SHELLS EXPLANATORY PRINCIPLE. The concept of electronegativity may be seen as allowing learners to move beyond the dichotomous classification *of elements* as metal/non-metal, and consequently to allow a classification *of bonding* with various degrees of polarity, rather than covalent/ionic.

However, in this research it was found that some of the colearners would *attempt* to rationalise polarity in terms of octets. At the end of her first year Jagdish discussed the polarity of a bond as being due to the extent to which the elements involved "pull electrons in a bond" (J3.A136), but she was only able to construe this in terms of the more electronegative element having to take electrons to form a full outer shell (see appendix 33, §A33.8.1). Similarly, when Noor gave an account of electronegativity at the end of her first year her explanation was in terms of octets and only discriminated metals from non-metals,

> "in all cases what an atom is trying to do is to become stable, and so, er, obtain a *full outer shell*. In the case of metals it's easier for them to become stable by losing electrons, and, by doing this they become positive, so they're gonna be more electropositive, whereas [non-metals] to become stable, erm, would acquire those electrons, and hence become more electronegative, 'cause they've gained electrons"
> N3.A150

At the end of Kabul's his course he understood the most electronegative and electropositive elements to be those that needed to gain or lose the least *number* of electrons to gain an octet (see appendix 33, §A33.8.2).

§11.2.8: Stable electronic structures.

Although the FULL SHELL EXPLANATORY PRINCIPLE is used by colearners in ways that are here considered invalid (such as a rationale for chemical reactions occurring, and artificially distinguishing between equivalent between-ion interactions in lattices), and although it may be considered to act as an impediment to progression (as it does not provide a basis for understanding bond polarity or hydrogen bonds for example), it is none-the-less based on an established principle from CURRICULUM SCIENCE, that some electronic structures appear to be associated with particular stability.

The noble gases were - and often still are - referred to as inert, as they tend to be unreactive. This may be explained in the following terms:

1. the noble gas atoms are electrically neutral, and therefore do not attract charged species (including polarised species) at a distance.
2. the charge distribution of a noble gas atom is symmetrical so that the atom 'presents' no permanent areas of higher negative or positive charge (i.e. the electron cloud is equitably distributed, and the nuclear charge is effectively shielded).
3. the noble gases do not have any singularly occupied orbitals in the ground state that can overlap with orbitals on other atoms to form lower energy molecular orbitals, and thus bonds. (The exclusion principle does not allow them to overlap in the ground state.)
4. the noble gases do not generally have available empty orbitals suitable (in particular at similar energy level) for promoting electrons to provide singularly occupied orbitals for overlap.

Points 3 and 4 refer to the energetic (thermodynamic) considerations that may be understood as the driving force for reactions. Points 1 and 2 refer to the mechanisms by which species may interact.

Point 1 applies to all atoms, of course, but point 2 does not, because the distribution of charge in an atom is restricted by quantization: that electrons must occupy orbitals that are solutions to the Schrödinger equation. Point 2 would therefore not apply to any atom that had sub-shells that were other than full, or half-full. In other words configurations such as s^1, s^2, p^3, p^6, d^5, d^{10} etc., would be inert in these terms. However point 3 would suggest that s^1, p^3, and d^5, configurations would be relatively inert, but not particularly stable. However one would expect particular stability to be associated with configurations such as s^2, s^2p^6, s^2d^{10}, $s^2p^6d^{10}$, and generally this what is found. That point 4 is not absolute is reflected in the existence of several compounds of the heavier inert gases.

This analysis is somewhat sophisticated and may be too subtle for some A level students. This is reflected in the colearners' applications of the FULL SHELLS EXPLANATORY PRINCIPLE. Lovesh thought that is was not possible for one sodium atom to exist alone as it did not have a full outer shell (see appendix 33, §A33.9.1).

In Lovesh's final interview, near the end of the second year of his course he explained how a sodium atom is not stable "because it hasn't got a, a full outer electron shell, [the] outer electron shell hasn't got eight electrons in" (L4.A067). Indeed Lovesh thought that "it's not possible to have one on its own" (L4.A26). Other colearners also suggested that single atoms would not be stable where they did not have full shells (see appendix 33, §A33.9.2).

§11.2.9: Ionisation energies.

The FULL SHELLS EXPLANATORY PRINCIPLE criterion of atomic stability may be seen to effect learners' understanding of ionisation energies.

So, for example, Lovesh had studied patterns in ionisation energies, but when asked about the stability of the sodium ion he appeared to be operating from his FULL SHELLS EXPLANATORY PRINCIPLE perspective, and he did not think a second ionisation of sodium was possible (see appendix 33, §A33.10.1).

Data collected from students' responses to a past examination question about ionisation energies reflected the same perspective. It would seem that when a question concerns one of the noble gases then the observed stability of the noble gas electronic configurations may be invoked as an explanation, rather than as a phenomena to be explained. The question, used in the end-of-first-year examination given to A level chemistry students in June 1994, asked *why neon had the highest molar first ionisation energy of the elements in period 2*. The most appropriate answer from a curriculum science perspective would focus on the core charge, which increases across the period. However, even when this *is* invoked, the full outer shell status may also be mentioned as another reason. A number of students, however, gave a response that suggested that the high ionisation energy could be explained completely in terms of the FULL SHELLS EXPLANATORY PRINCIPLE. Once again the precise wording varies considerably, with *full shells*, *eight electrons*, *octets* and unspecified *stable configurations* variously used to make the point (see appendix 33, §A33.10.2).

The theme of this thesis is *Understanding Chemical Bonding*, and *ionisation energy* could seem to be something outside of this topic (although ionisation energy is a term in the Born-Häber cycles that also includes the energy changes on bond formation such as lattice energy). However, it would seem that in this research learners may construe ionisation energy in terms of the same FULL SHELLS EXPLANATORY PRINCIPLE used to explain bonding itself. Moreover, whereas in explaining the inert behaviour of the noble gases, arguments that these atoms have 'full shells' or 'octets' could be considered as an oversimplification of the analysis in points 1-4 given above (§11.2.8), in the case of ionisation energy it is much clearer that explaining the high first ionisation energy of neon in these terms is clearly *not* a less sophisticated version of CURRICULUM SCIENCE. Where Lovesh's comments about sodium are concerned, it is seen that the FULL SHELLS EXPLANATORY PRINCIPLE is applied, even though it leads to a prediction that clearly contradicts work Lovesh has previously studied.

Appendix 3 gives details of a pencil-and-paper that was developed to diagnose the extent of some of the alternative notions about ionisation energy elicited from learners in this study. The TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT was used with a sample of 110 A level chemistry students who had studied the topic of ionisation energy.

The responses to some of the items in the instrument suggested that the application of a FULL SHELLS EXPLANATORY PRINCIPLE is much more widespread than just the colearners in the interview study. The respondents were shown a copy of focal figure 1, and 35% of respondents thought, like Lovesh above, that *only one electron can be removed from the atom, as it then has a stable electronic configuration*. 75% of respondents agreed with the statement that *the atom would be more stable if it 'lost' an electron*, and 56% of respondents agreed that *if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration*, although presumably they were aware that positive and negative charges attract each other.

Perhaps most significantly 83% of respondents agreed that *the atom would become stable if it either lost one electron or gained seven electrons*. If these students were interpreting the statement as intended, they were overwhelmingly suggesting that not only would Na^+ (electronic configuration, 2.8) be stable, but so would the species Na^{7-} (electronic configuration, 2.8.8), which is highly unstable from a CURRICULUM SCIENCE perspective. In case this last result was due to an ambiguity in the statement, a separate question about atomic stability was prepared and presented to a class of A level chemistry students (further details are again given in appendix 3). They were asked to compare the stability of the three species concerned,

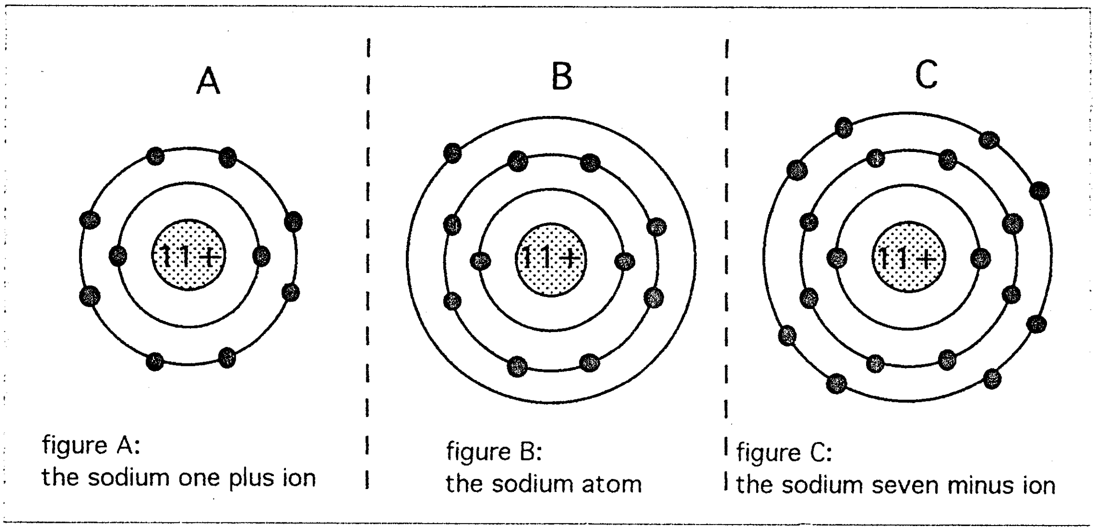


figure A:
the sodium one plus ion

figure B:
the sodium atom

figure C:
the sodium seven minus ion

three figures used to elicit views on chemical stability (reproduced at 75% of original linear dimensions)

Ten students in this class (63% of respondents) thought that "B is less stable than C", a conclusion that may follow from the FULL SHELLS EXPLANATORY PRINCIPLE, but gives scant regard to a consideration for electrical neutrality. The association of full shells/octets with stability was clear in the respondents explanations, such as,

> B is less stable than C because ... the outer shell of C is full with eight electrons but B only has 1 electron in its outer shell and is less stable.
>
> B is not as stable as C because it needs [sic] another 7 electrons to fill the outer shell

In the comparison between the sodium atom and the cation, 13 students (81%) thought the cation more stable, and only 1 thought it was less stable than the atom, again reflecting the responses to the DIAGNOSTIC INSTRUMENT, and again ignoring the CURRICULUM SCIENCE principle that in the absence of an effective electron acceptor the neutral atom would be a stable species.

When the same question was used as an induction exercise with a class new to A level work, the option *B is less stable than C* was selected by 11 of 13 respondents (85%), and the same number of respondents also selected *A is more stable than B.*

One of the explanations given makes a fitting quotation to underline this section on how the octet rule is used by learners as an explanatory principle,

> "If an atom has been filled up or all ready full up (of 8 outer electrons) it becomes stable and therefore it is unreactive. The atom will stay that way forever and not react or loose or gain any electrons."
>
> (A level student, written induction exercise, September 1995.)

§11.3: The use of anthropomorphic language to discuss atomic phenomena.

> "This reaction occurs because both Hydrogen and Oxygen atoms *wish* to become stable. By bonding they both become stable. Hydrogen now has 2 electrons in its first and outer shell, oxygen now has 8 electrons in its outer shell; so both are chemically stable. At first neither the Hydrogen (H) or oxygen (O) atoms are stable. Each Hydrogen atom *needs* one more electron in order to be stable (i.e. have 2 electrons in first shell). The Oxygen atom already has 6 electrons in its outer shell, so *needs* 2 more in order to be stable (i.e. 8 electrons in outer shell.) The atoms now bond covalently, by both Hydrogen atoms *sharing* 1 electron, and oxygen by *sharing* 2 electrons."
>
> (Induction exercise, September 1995.)

Whereas CURRICULUM SCIENCE provides a mechanism for chemical processes to occur, i.e. electrostatic forces, the FULL SHELLS EXPLANATORY PRINCIPLE is not associated with any particular type of force. In the interview study it was found that colearners tended to give explanations based on this principle in language that was anthropomorphic. That is, atoms were spoken of *as if* they were sentient actors that had perceptions and desires, and were able to act accordingly. Such language may represent either anthropomorphic *thinking* on the part of the learner (thinking in terms of the atom being a sentient actor), or alternatively, a ***metaphorical*** description where the best way the learner can find to explain their thinking is to speak *as if* atoms were conscious agents.

Some of the language used by colearners in the interviews, which *could* be considered as anthropomorphic, might be better classified as 'dead metaphor', i.e. terms that at one time had metaphorical weight, but with familiarity of use have taken on a new, and now literal, meaning. It could certainly be argued that in chemistry the notion of atoms *sharing* electrons in bonds is an example of such usage. For electrons to be *shared*, *donated* or *accepted* by atoms implies some sense of *ownership* - a concept relating to human social affairs - and this may be considered to have originally been a way of conceptualising molecular systems *by analogy with* human experience. As these terms are accepted and ubiquitous in chemistry, it would be inappropriate to suggest that they are evidence for anthropomorphic thinking among my colearners. Rather, these terms are akin to technical terms that soon become habitual when reading and talking chemistry. It is suggested that the widespread use of these terms has more significance for the construction of learners' atomic ontologies (as discussed earlier in this chapter, §11.1), than for being evidence of their anthropomorphic thought.

Other language used by colearners, however, such as suggesting that atoms 'like', 'want' or 'need', should not be explained as dead metaphor. There were many examples of such comments in the data collected from colearners, and the extent and range of contexts of anthropomorphism may be gauged from the examples below. In some cases this use of language was actually discussed with the colearners to explore their awareness of the anthropomorphisms (§11.3.3).

§11.3.1: What atoms want: anthropomorphism in place of physical mechanisms.

The emphasis placed on colearners' anthropomorphic language in this thesis is due to the way such language seemed to stand in place of physical causes. In other words, it often seemed that when a colearner suggested that a bond formed because that was *what atoms wanted*, the colearner did not seek to look for an alternative explanation.

The extent to which having an anthropomorphic 'explanation' impeded the learner's quest for a physical explanation, rather than just being used because no alternative was available, or due to habit, is a question that may benefit further research (see chapter 12, §12.6). However, it is clear that a great deal of anthropomorphic language was used by learners, and much - although by no means all - of this was related to the application of the FULL SHELLS EXPLANATORY PRINCIPLE Put simply colearners suggested that *bonds form because atoms want to have full shells*.

One common way in which the FULL SHELLS EXPLANATORY PRINCIPLE was applied by the colearners was by referring to how atoms *needed* to acquire (or lose) electrons to become stable (see appendix 34, §A34.1.1). Other examples of this use of 'needs' were found in incidental data collected from other chemistry students. The following explanation of the reaction between oxygen and hydrogen involves the assumption that the reactants are *atoms* (see §11.1.1), and refers to their needs, the 'needed' noble gas structure, and the sharing of electrons that satisfies the atoms,

> "This reaction occurs due to the covalent bonding which takes place. Hydrogen *needs* an extra electron to *copy* He [helium] and have a stable condition. Oxygen *needs* two electrons, and so two hydrogens and one oxygen bond together covalently so that each hydrogen *shares* an electron with oxygen so that their outer shells are all stable."
> (Induction exercise, September 1995.)

However a range of other examples were also uncovered (see appendix 34, §A34.1.2) In the following example, 'require' is used rather than 'need',

> "oxygen has 6 outer electrons so it *requires* another two electrons to fill the outer shell. Hydrogen has 1 spare electron so 2 hydrogen electron is *required* to fill oxygens outer shell [by] combining to make a full shell.
> (Induction exercise, September 1995.)

A way of expressing similar ideas was in terms of the slightly less imperative reference to what an atom 'wants'. Again this was used widely amongst the colearners in this study, as when Kabul suggested that chlorine "*wants* to become a stable atom" (Kabul, K6.A322), but there were many other examples (see appendix 34, §A34.1.3). Again this use of anthropomorphism was reflected in incidental data collected from other learners' course work (see appendix 34, §A34.1.4) as in the examination answer suggesting that an aluminium ion "*wants* to have a full shell". For most learners there is probably little significance to the choice of 'needs' or 'wants', despite the literal difference in meaning, and there were examples in the data collected where the two words seemed to be used interchangeably (see appendix 34, §A34.1.5).

Besides 'need' and 'want', the colearners interviewed used a number of other similar terms (so that atoms "*like* to achieve a stable noble gas configuration" and "*prefer* to have eight electrons") implying that atoms had human feelings (see appendix 34, §A34.1.6). Once more, similar examples (such as the hydrogen atom that was "*very eager* to get the 1 electron to complete its outer shell") were found amongst other chemistry students (see appendix 34, §A34.1.7).

Tajinder (chapter 8) sometimes referred to atoms 'thinking', and in particular that bonding took place so that the atoms could 'think' they had full shells (see appendix 34, §A34.1.8). As far as achieving full shells was concerned, Tajinder suggests that it is indeed the atom's perception of its octet status which is critical, so when aluminium chloride formed a dimer "the aluminium ***thinks*** that it's stable because it's got eight outer electrons, but really it hasn't, but it ***thinks*** that it has" (T10.A524).

So, according to the colearners, atoms *want*, or even *need* full shells, and according to Tajinder at least they are aware of their octet status or otherwise. Some colearners also talked as though the atoms then deliberately went about obtaining full electron shells. As Noor and Tajinder both explained, "in all cases what an atom is *trying* to do is to become stable, and so obtain a full outer shell" (N3.A150), or "all elements *try* to gain noble gas configurations to become stable" (T4.A062). There were other references to atoms 'trying' in the interviews (see appendix 34, §A34.1.9) and in the incidental data collected from other students (see appendix 34, §A34.1.10).

§11.3.2: Anthropomorphism in other contexts.

I have demonstrated, above, that learners' discussions of bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE are often anthropomorphic. I have argued that the FULL SHELLS EXPLANATORY PRINCIPLE is by its very nature anthropomorphic, in that anthropomorphic language stands in place of the physical mechanisms which explain bonding processes in CURRICULUM SCIENCE. Further, it may be conjectured that *without* the availability of such anthropomorphic language the limitations of explanations of bond formation in terms of full shells would be clear to learners, and thus this mode of discourse may be a factor inhibiting their progression towards alternative explanatory schemes with more currency in CURRICULUM SCIENCE.

It is therefore illuminating to consider whether learners' anthropomorphic explanations about bonding and related phenomena are limited to arguments based on the FULL SHELLS EXPLANATORY PRINCIPLE. In the present research it was found that whilst anthropomorphic language was widely used in explanations based on full shells, it was also commonly used in other types of explanation. The interaction between electrical charges was often discussed in anthropomorphic terms by the colearners, in particular with various species said to be *trying* to attract or get apart from one another (see appendix 34, §A34.2.1). Further examples of anthropomorphic language used to describe electrostatic phenomena were collected from the end-of-first-year examination given to A level chemistry students in the College in June 1994 (see appendix 34, §A34.2.2). These various examples of learners explaining electrostatic interactions as though charged particles are sentient actors should be considered in the context of the evidence presented in the previous chapter (chapter 10) which suggests that chemistry learners may be ignorant of fundamental ideas in electrostatics. The anthropomorphic explanations of bonding based on the FULL SHELLS EXPLANATORY PRINCIPLE may be considered part of a wider tendency to discuss electrostatic phenomena as though due to the desires and deliberate actions of charged species.

Chapter 9 demonstrated that learners may find some quantum ideas difficult to grasp, and this is another area where colearners in this study were found to use anthropomorphic language, so that Edward suggests that "an electron always *tries* to achieve its ground state" (E2.A157). A number of other examples were elicited during the interviews (see appendix 34, §A34.2.3).

§11.3.3: The extent of learners' awareness of their anthropomorphic language.

In view of the widespread use of anthropomorphic language found in this research, it is important to know whether learners mean their anthropomorphic expressions to be literal or figurative. On some occasions during the interviews this aspect of some of the colearners' talk was probed.

In her second interview Debra suggested that a covalent bond would hold atoms together "because they, they gain the full shell then, so they're stable molecules, so it's sort of *desirable* to be like that" (D2.111). The anthropomorphic aspect of this suggestion was challenged. Debra's response is interesting because although she refers to minimising energy, and a "random" process, she seems to accept the anthropomorphic language of the question. Indeed even when her comments are interpreted *in situ* as negating the suggestions of a sentient atom, Debra herself seems less sure,

> I: Do you think the carbon atom is *aware* of the fact that it's got four electrons in its outer shell? And *aware* of the fact that it's *desirable* to have eight? And so is it some sort of *tension* that makes it go round and *search out* electrons and when it's got eight it *says*, 'right, I can relax now'?
>
> D: Yeah, if, if the erm energy of the sort of molecule would be lower than the energy of you know when it's, on its own, it will.
>
> I: But does the carbon *actively seek* to do this?
>
> D: No, it's sort of random.
>
> I: So it's not like a carbon atom's got some sort of *consciousness*, of a very low level, whereby it has some sort of *awareness*, that it's missing some electrons, and it *actively seeks* them out, and when it gets them it *says* 'right, that's it - work done for the day'?
>
> • •
>
> D: I don't know.
>
> I: Does that sound feasible for a carbon atom, to sort of > work in that mode? >
>
> D: < Well, < not really, no.
>
> D2.114

Edward used anthropomorphic language when asked to explain his comments about noble gas configurations. He explained that on "ionic bonding, and covalent bonding as well" atoms,

> "*like* to achieve a stable noble gas configuration. Which are, two in the first shell, eight in the second, and it goes up according to $2n^2$, depending on the shell."
>
> E1.231

He explained this with a tautology, that "each orbital in each shell is filled, and it doesn't *need* to acquire electrons, or, lose electrons, to fill all its shells" (E1.233). Edward was asked for further explanation. At first Edward seems to be going to repeat his tautology that the atom "doesn't require anything else" (E1.235), but he switches to an anthropomorphic response, that "atoms are, *happiest* ... when they've got full orbitals. And ... that's what they always, *try and, achieve*" (E1.235). Edward considers that somehow atoms are aware of their electronic configurations, and are active agents in seeking full shells (E1.237), but is unable to suggest what form this awareness may take (E1.238-45, see appendix 34, §A34.3.1). Edward was then asked if it is reasonable that atoms should somehow have a kind of awareness, and he still thought it was (E1.249), although he did not believe atoms could think (E1.253). On further questioning Edward suggested that "there has to be some mechanism" (E1.265) by which the atoms could form a molecule, and suggested "it must be something to do with the achieving a sort of equilibrium charge, force ... between the, particles" (E1.273). Edward still thought there was a requirement of the 'full shells' type, as "electrostatic" forces (E1.294) "would pull all the electrons in, closer to the nucleus, so that all these levels were filled, from the nucleus outwards", as,

> "in the atom [there are] defined orbitals and if the nucleus attracts the electrons, then there's going to be a vacancy outside the last electron to be attracted. And these *need to be filled*"
> (E1.296).

In the fourth interview, near the end of his course, Lovesh made a similar remark, but when probed was able to explain his point in terms of an electrostatic argument,

> I: Erm, is that [focal figure 1, a sodium atom] a stable species, do you think?
> L: Erm,
> • • • (pause, c.3s)
> L: no, because it hasn't got a, a full outer - electron shell, outer electron shell hasn't got eight electrons in.
> I: So if it's not stable, what would tend to happen to that, do you think?
> L: It will *wanna* donate the electron to another atom.
> I: Right, when you say 'it wants to donate' it?
> L: Erm.
> • • •
> L: Well because that outer electron is less attracted to the nucleus, erm it is, it can easily be transferred, attracted by another atom.
> L4.A067

In Jagdish's third interview she was able to consider the stability of a sodium atom to be relative to its surroundings: its valence electron would not be removed unless there was some nearby agent to apply sufficient force. *However* she continued to use anthropomorphic references, that the atom might *want* to form a lower energy level, and would *give* away its electron (J3.A345).

As Jagdish had just been applying an electrostatic framework to answer questions I was interested to find out whether her subsequent use of anthropomorphic language was just a habit of speech or amounted to an active explanatory framework. I asked a question posed in similar anthropomorphic language, (i.e., 'were there things the atom *wanted to do even more* than form compounds?') to see how the response would be framed. Jagdish initially seemed to ignore the anthropomorphism, and answered in terms of forces (which might suggest her anthropomorphic use of language was indeed habitual), but then concluded with a further anthropomorphism, that the atom was "just happy on its own" (J3.A359).

I then attempted to test the extent to which Jagdish would continue to accept such language by presenting a range of alternative anthropomorphisms for her to accept or reject: did the atom *desire*, *enjoy*, *get its kicks*, *reflect*, *consider*, *decide*? As Jagdish appeared to accept all these alternatives (see appendix 34, §A34.3.2), a further attempt was made to find the extent to which these terms were being used as metaphor, by challenging their literal meaning: I asked Jagdish how the atom knew it wanted to form compounds: had it been told, or had it worked it out for itself? Her answer alluded to physical interactions, but also suggested that the atom can *know*, *realise* and *want* (J3.A385). Jagdish thought the sodium atom's realisation of the presence of a chlorine atom required close proximity, so the sodium would *feel* the chlorine (J3.A385). Despite this *feeling* Jagdish did not think a sodium atom would make a conscious decision to interact with another species: it just happened (J3.A432).

Later in the interview, the extent to which the atom had feelings was revisited. At first Jagdish seemed to find the anthropomorphism acceptable, but as stronger examples were suggested she seemed to start to have doubts. So she agreed that the atom *desired* to form a compound, although she did not think it got lonely (J3.A508). Whether the atom would get jealous "depends on how reactive that particular ... atom is compared with the, other atom that has formed a compound" (J3.A508). She thought that an atom might feel envious, "*if* you can say that about an atom" (J3.A520). Jagdish did not think the atom would feel hate, and *at this point decided the atom had no feelings* (J3.A520).

Yet later still in the interview, Jagdish agreed with suggestions that an atom would *prefer* to have eight electrons; would *want* to have eight; and that it *wanted* to get another atom's electron (J3.B352). Once again Jagdish was quite comfortable with the use of anthropomorphic description, but when the sentience of the atom was queried she said that "it doesn't know" that it needs another electron (J3.B355). Instead of the anthropomorphic rationale Jagdish gave an alternative explanation in terms of energy levels (J3.B355), but then commented that being at a lower energy level was "what they all *want*" (J3.B361). Once again Jagdish had switched back to anthropomorphic language.

At the end of this interview Jagdish was discussing the hydrogen molecule and suggested that "all the atom *wants* to do is ... it just *wants* to, neutralise the core charge" (J3.B437). This was the last episode in the interview, which therefore concluded with Jagdish referring to electrostatic factors, but in terms of an anthropomorphic framework of language. (This aspect of Jagdish's explanations is described in more detail in appendix 34, §A34.3.2).

During Kabul's fifth interview he referred to the delocalised electrons in a metal in an anthropomorphic way (wandering around), although he realised this and corrected himself - they only appeared to be wandering, but that was just the way it looked (K5.A206, see appendix 34, §A34.3.3).

Kabul also seemed aware of his use of anthropomorphism when discussing how orbitals could get hybridised if they *wanted* to (K5.A347). Kabul claimed that this use of "wants" was not literal, but "just theories ... to make our life simpler" (although it was not clear whether the degree of metacognitive awareness Kabul had of his use of "*they want*" also extended to his use of "*they need*", see appendix 34, §A34.3.3), and he was satisfied with this level of description (K5.A361).

In his final interview, during the last term of his course, Kabul referred to stable species being *happy*, and again when this was queried he seemed to feel the description was appropriate. Later in the interview Kabul referred to how "an oxidising agent ... *tries* to pull electrons away" from a sodium atom (K6.A243), which is "quite *happy* to give it away, because it comes more stable" (K6.A246), and how "an oxygen atom ... has got six outer electrons ... so they, each oxygen, has *needs*, ... [for] 2 electrons to become more stable so you know they form the octet" (K6.A243). When Kabul's notion of atomic happiness was again challenged he was unable to explain what form this took. He at first suggested that the atom *was* aware, although not consciously so, rather "it just happens", as if by magic (indicated by the clicking of Kabul's fingers, K6.A259). Kabul then decided the atoms were "not really" aware, and reiterated that "it just happens" (K6.A268).

Later in the interview Kabul referred to how a dative bond would form between $AlCl_3$ molecules "to obtain the octet state because octet state is usually stable" (K6.B128). The molecule *knew* it had not got an octet state as, "it's unstable, it's not aware, you know, physically, but, you know, it would *prefer* to have eight electrons" (K6.B135). Kabul thought that 'prefer' meant something "different" (K6.B135) for atoms than for people, but he was not able to explain this any further. (This aspect of Kabul's explanations is described in more detail in appendix 34, §A34.3.3).

So the cases of the individual colearners appear to be different in the degree of metacognitive awareness of their anthropomorphic language. Jagdish was comfortable with the most blatant anthropomorphisms (atoms *enjoying* and *desiring* and being *jealous*), but denied that atoms had feelings when asked directly. Kabul also seemed comfortable with language of this type but was aware that it was figurative, a way of making expression simpler. However, his awareness of the lack of literal meaning of expressions such as the 'the atom wants' did not make such terms problematic for him. He accepted these terms were "just theories", but perhaps for Kabul these theories that "made life simpler" had similar status to the theories of CURRICULUM SCIENCE, such as acid-base theory, redox, and kinetic theory. This issue is considered more in the discussion section (§12.4.4).

§11.4: Significance assigned to electronic history: the history conjecture.

> "it would seem a bit of an odd-ball, wouldn't it, to have somebody else's electron"
> (Paminder, near the end of the first year of her A level course, P3.A428).

Another aspect of learners' thinking identified in the interviews was the implicit suggestion that the history of an electron is significant. This could be seen as closely related to the notion of electrons *belonging* to atoms (discussed above, §11.1.4): for if electrons belong to particular atoms then it might be important to identify which atom an electron came from, and therefore belonged to.

The notion of molecular biography is obviously closely related to the theme of the previous section (§11.3), that is colearners tend to refer to chemical systems anthropomorphically. As was pointed out in chapter 3 (Benfey's analogy of molecular life-histories, §3.1.4), anthropomorphic and animistic references are not uncommon in scientific writing, and are not problematic when their metaphorical role is recognised (c.f. §11.3.3). This present section considers the significance that learners ascribe to such history when they do not recognise the limits of the analogy.

One consequence of the history conjecture is an assumption that when a bond breaks atoms *get their own electrons back*. The history conjecture may also lead to the ionic bond being defined in terms of the donation and acceptance of an electron between atoms, rather than an interaction between ions. This in term may support the 'misconception' that there are molecules in ionic materials (§3.2.6).

The assumption that an electron's history, or perhaps biography, is significant can not be explained in terms of electrons being seen as different to one another. In general the colearners in the study accepted all electrons were the same. An exception was Annie, who suggested in her first interview that electrons might "actually contain some of the element in the electron" (A1.138). She thought that the size and charge of the electrons would be different for the different elements (A1.144-150). However, such a view was not reflected by the other colearners, and their tacit assumptions about the importance of electronic history can not be explained in this way.

§11.4.1: Bond fission.

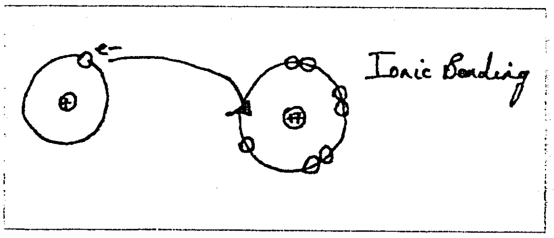
When colearners discussed bond-breaking in contexts such as focal figure 3 (representing a molecule of tetrachloromethane) they sometimes specified that the electrons would return to the atoms from which they originated. According to CURRICULUM SCIENCE there is no reason to expect this, nor any mechanism to explain such a phenomenon. Notwithstanding CURRICULUM SCIENCE, learners in the study *expected* the electrons to return to the appropriate atom. Perhaps, as Paminder suggests in the motto above, the alternative seemed 'odd'. Atoms were said to take the electrons they had given in the first place, their own electrons, or the electrons which belonged to them (see appendix 35, §A35.1.1).

In some cases no rationale for these suggestions was offered beyond which electron belonged to, or originated in, which atom. So in Kabul's first interview he knew "there wasn't any difference" between electrons, but confirmed that they would go back to the 'right' atoms (K1.A270). Although he accepted that the "atom has no idea" which electron to take back, Kabul thought it would get the 'right' electron back (K1.A274). However, by the end of the first year of his course, Kabul had constructed an explanation for this phenomenon, based on electron spin, that was quite ingenious, although ultimately invalid (see appendix 35, §A35.1.2). The significant point here perhaps is that Kabul had become aware of, and concerned about, the lack of a physical reason to explain his belief, and rather than dismiss the notion that electrons return to their own atoms, he had developed a rationale to justify it. When he was persuaded that this argument did not work, Kabul was then prepared to accept that on bond breaking "either" electron would go to the chlorine atom (K4.383).

Several of the colearners explained why an atom would 'get its own electrons back' on bond fission in terms of there *only* being a force, or there being a *greater* force between a nucleus and its own electrons (see appendix 35, §A35.1.3). Again in these cases 'octet thinking' seems to take precedence over electrostatic ideas.

§11.4.2: Ionic bonding seen as electron transfer.

In CURRICULUM SCIENCE terms ionic bonding is the force holding cations and anions in a lattice. However, in the research it was found that mention of ionic bonding to learners was most likely to elicit comments about *electron transfer* to *form* ions, in addition to, or in precedence to, or even in place of, consideration of the electrostatic forces between ions. Indeed, a great deal of evidence was collected in the research to support the view that at the start of an A level course the ionic bond *is* commonly identified with the electron transfer event conjectured to be required for ion formation (see appendix 35, §A35.2.1). For an example, in Noor's first interview for the research she explained ionic bonding in terms of an electron transfer event, where atoms attempted to satisfy the FULL SHELLS EXPLANATORY PRINCIPLE, that is "ionic bonding *is* the *transfer of electrons* from one atom to another, and ... the aim again is to try and get, erm, complete outer shell" (N1.A300). During her first term she depicted ionic bonding as an electron transfer event between isolated atoms,



Noor's diagram of ionic bonding, November, 1992.

Noor may be seen to be making the *assumption of initial atomicity* (§11.1.1), and the data collected suggests that when asked to think about ions, many students do so by thinking first of atoms, and then considering ion formation from the atoms.

From the many similar statements (and diagrams) presented in the appendix (appendix 35) it may be inferred that the ionic bond was typically seen by the colearners as an electron transfer event between discrete atoms, to give ions with stable electronic configurations. The colearners' discussions of ionic bonding are consistent with the FULL SHELLS EXPLANATORY PRINCIPLE, and are conceptualised in terms of discrete atoms (i.e. making an assumption of initial atomicity).

When students study ionic bonding at A level the main concept presented is that of a lattice of cations and anions bound by *electrostatic forces*. The colearners in the present study acquired this perspective to varying degrees. However, as was illustrated in chapter 10, the underlying electrostatic principles inherent in the CURRICULUM SCIENCE model were not always familiar to the colearners.

It was reported above (§11.4.1) that several colearners thought that in a covalent bond the individual electrons would be attracted more strongly by their 'own' atom. It was also found that Kabul only thought two ions could attract if there had been electron transfer between them, so that two counter ions in solution would not attract, as "attraction is only possible when a bond is formed" (K3.A056). For Kabul the close proximity of a positive ion and a negative ion was not sufficient for a bond to form between them (see appendix 35, §A35.2.2).

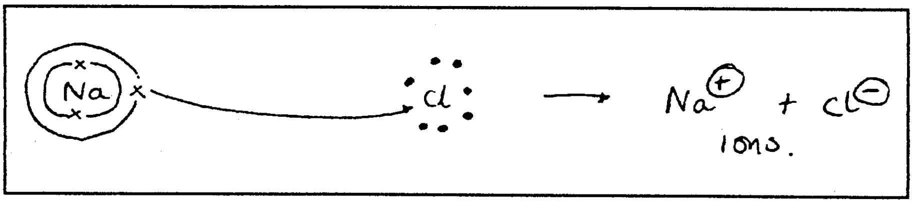
As the case study of Tajinder in chapter 8 demonstrates, learning the electrostatic explanation does not imply discarding the 'octet' rationale. Indeed there is evidence from the data collected that colearners often continued to see the ionic bond - at least primarily - in terms of electron transfer between discrete atoms, after they had been taught during their A level course that the bond was an electrostatic interaction between ions (see appendix 35, §A35.2.3). So ionic bonding continued to be defined as "complete transfer of, an electron, to another atom" (C3.646), when "one of the atoms loses its electrons and the other atom gains that electron" (K4.A512) and as "when one atom transfers electrons to another atom, completely, *to form* positive cation and negative anion" (L3.A025).

Among the colearners in the present study the ionic bond concept was often closely associated with, if not identified with, an electron transfer event, even after being taught at A level from the CURRICULUM SCIENCE perspective. Incidental data collected from induction exercises with other learners suggests that the definition of the ionic bond in terms of electron transfer - e.g. "ionic bonding is the transfer of electrons from one atom to another" - is common at the beginning of an A level course (see appendix 35, §A35.2.4). The focus in these definitions is with the ***needs*** (c.f. §11.3) of atoms to gain or lose electrons, and the bond is seen as (or intimately tied to) the resulting electron transfer events.

Similar features may be found in examples of the work from students near the end of their A level studies. For example the following definition of ionic bonding assumes discrete atoms as a starting point, focuses on electron transfer, and includes an explicit reference to full electron shells,

> "Ionic - forms lattice of Cations and Anions where *electrons are transferred* attaining full outer shell of e^{-}"
> (concept map, 2nd year student, May 1992.)

In a mock A level examination (March 1994), some of the students' explanations of the bonding in sodium chloride demonstrated the same features (see appendix 35, §A35.2.5). The same concerns were represented graphically by some candidates, for example:



"Sodium chloride - ionic bonding in this solid:-
As the Sodium has an electron in it's [sic] outer shell it can donate this electron to the chloride to form a stable ion with a full outer shell."

(Mock examination response, March 1994.)

Some responses that did mention the electrostatic forces, still *focused* on electron transfer (see appendix 35, §A35.2.6).

Appendix 2 describes a simple pen-and-paper instrument (the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT) used in the research to test whether some aspects of colearners' thinking elicited in this study were more widespread. The instrument was used to test a sample of 81 A level students who had not yet studied bonding at that level, and 128 who had (see appendix 2 for details). One of the statements presented in this instrument (item 24) was that:

> "an ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells"

Over four-fifths of those surveyed before being taught about bonding at A level agreed with this definition of the ionic bond, and over half of those who *had* been taught the topic at A level also thought the statement was true (see appendix 2, table A2.4). Although the sample used was quite small, and can not claim to be fully representative of A level chemistry students in general, this small scale survey does suggest that a molecular interpretation of ionic materials may be common.

§11.4.3: References to ionic molecules.

According to CURRICULUM SCIENCE the concept of the molecule is *not* relevant to ionic materials, where there is an extended lattice of ions. However, in the present research it was found that the particular ions that were conjectured to have been involved in a specific electron transfer event were sometimes considered to be a molecule. A number of the colearners explicitly referred to molecules in sodium chloride (Annie, Brian, Jagdish, Kabul, Tajinder and Umar, see appendix 35, §A35.3.1).

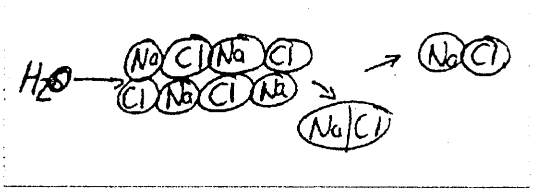
Brian thought that in the sodium chloride lattice each ion was part of a molecule with *each* of its neighbouring counter ions (B2.40), but in general a molecule of sodium chloride was conceptualised in terms of an ion-pair within the lattice.

Several colearners were able to nominate which ions in a diagram were meant to be in the same molecule. One colearner, Kabul, at one point suggested that there were ionic bonds within a molecule (i.e. ion-pair), but covalent bonds between the molecules (K2.A581) in potassium fluoride. Even at the end of her course Annie referred to a molecule of sodium chloride comprised of two atoms (A3.30).

So in this research study several of the colearners specifically referred to molecules in the context of ionic bonding. 'Incidental' data collected from other learners shows that the notion of ionic molecules is not restricted to the colearners interviewed for this research (see appendix 35, §A35.3.2).

Students may then see the dissolving of ionic materials in terms of the solvation of molecules (i.e. ion-pairs) rather than ions,

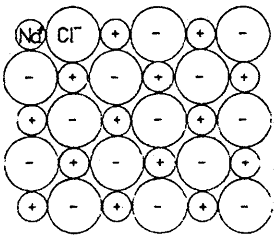
> [Sodium chloride dissolves in water] "because the water breaks up the large salt crystall [sic] into tiny *molecules of NaCl*, I don't think that any atomic changes go on in this process."



(Induction exercise, September 1994.)

References to sodium chloride molecules were identified in scripts for a mock A level examination, and in particular that the molecules were held together in the solid by van der Waals' forces (see appendix 35, §A35.3.3).

Appendix 2 describes a simple pen-and-paper instrument (the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT) used in the research to test whether some aspects of colearners' thinking elicited in this study were more widespread. The instrument was used to test a sample of 81 A level students who had not yet studied bonding at that level, and 128 who had (see appendix 2 for details). Four of the thirty items in this instrument related to the presence of of molecules in focal figure 5:



focal figure 5

The four items were:

7. In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion.
13. There are exactly fifteen molecules of sodium chloride in the diagram.
18. There is a bond between the ions in each molecule, but no bonds between the molecules.
29. There are no molecules shown in the diagram.

In each case a significant proportion of the responses supported the notion of molecules being present in the figure. Item 29, which denied the presence of molecules was considered 'false' by 59% of A level students who had not studied the topic at A level, and 46% who had. 50% of those who had not studied bonding at A level, and 46% of those that had, thought there were 15 molecules of sodium chloride in the diagram; and almost equal proportions 53%, and 52% respectively thought that the molecules contained one cation and one anion. Item 18, which suggested there were no bonds between the molecules, was supported by smaller proportions of respondents (36% of students who had not, and 22% of students who had, studied bonding at A level), but this item required students to accept the presence of molecules, *and* take a particular view of the interaction between them. Although the sample used was quite small, and can not claim to be fully representative of A level chemistry students in general, this small scale survey does suggest that a molecular interpretation of ionic materials may be common.

It would seem then that, on the basis of the evidence presented, the notion of ionic molecules, i.e. ion-pairs that are discrete units within an ionic lattice, may be widespread amongst A level chemistry students, even though it is not sensible from a CURRICULUM SCIENCE perspective.

§11.5: Electrovalency as the determinant of the number of ionic bonds formed: the valency conjecture.

If - from the 'octet perspective' - the electron transfer event is seen as an integral part of the ionic bond, such that ionic bonds can *only* occur where there has been electron transfer, then the number of ionic bonds that an atom may form is determined by the number of electrons it will donate or accept in reaching an octet state, i.e. by the electrovalency. A number of the colearners in the study (Carol, Kabul, Lovesh, Noor, Paminder and Tajinder) demonstrated the tendency to think along these lines at the start of their A level course (see appendix 36). Carol suggested that an atom could form as many ionic bonds "as it wants, *as long as it's got electrons to cover how many it does want*" (C1.262). Tajinder reported that in sodium chloride "one chlorine is only bonded to one sodium, because a sodium atom can only lose one electron, so, therefore ... it can only gain one bond" (T1.A446). In Paminder's first interview she reacted to a diagram showing sodium surrounded by four chloride ions (in a plane of the crystal structure) by demanding to know how that could be possible: "how can you have that when, *there's only one electron in the sodium, to give to one chlorine*, so how are these three, how are they attached to that?" (P1.A307).

Appendix 2 describes the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT, that was written to provide a pencil-and-paper test for some of the alternative conceptions elicited during the interviews with colearners. The valency conjecture would limit sodium and chlorine to forming one ionic bond each as their ions have charge of magnitude one. Several items in the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT related to this aspect of ionic bonding:-

2. Each chloride ion in the diagram is bonded to only one sodium ion.
4. A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.
10. Each sodium ion in the diagram is bonded to only one chloride ion.
14. In the diagram each chloride ion is bonded to more than one sodium ion.
17. A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.
21. In the diagram each sodium ion is bonded to more than one chloride ion.

The instrument was used with a sample of 81 A level chemistry students yet to study bonding at A level, and 128 who *had* studied the topic at this level (see the details in appendix 2).

Items 2, 10, 14 and 21 concerned the number of bonds each ion had in the lattice. The proportion of respondents supporting the view that each ion only had one bond varied in the range 37% to 46% for the four items amongst those yet to study bonding at A level, and in the range 14% - 28% for those who had. These four items did not specify the *type* of bond being discussed, and although from a CURRICULUM SCIENCE perspective the bonds would all be ionic, learners would not necessarily share this assumption.

Items 4 and 17 specifically referred to ionic bonds, and for these items a majority of respondents agreed with the valency conjecture viewpoint:

item number	item statement	support for *valency conjecture* before teaching	support for *valency conjecture* after teaching
4	A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.	57% selected TRUE	60% selected TRUE
17	A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.	60% selected TRUE	58% selected TRUE

percentage of A level students selecting responses supporting the valency conjecture

The sampling method was 'convenience sampling' (see appendix 2), and this survey can not be claimed as representative of the wider population of A level chemistry students. Also, there was no matching of the two samples of students before and after teaching, and therefore the close matching of the responses before and after teaching can not be considered too significant. Notwithstanding such caveats, this finding *suggests* that the notion that the number of ***ionic bonds*** is restricted by electrovalency may be one that is not readily 'corrected' by teaching. A more rigorous survey would be needed to confirm this. This point is considered in the discussion in chapter 12 (§12.6). The data presented certainly demonstrates that several colearners held a valency conjecture that clearly impeded their learning of the taught model of ionic bonding, and the small scale survey carried out with the diagnostic instrument suggests this may be a widespread feature of chemistry students' thinking.

§11.6: Dichotomous classification of bonding.

> "bonds can be either covalent or ionic"
> (Induction exercise, September 1991.)

The FULL SHELLS EXPLANATORY PRINCIPLE readily accommodates covalent and ionic bonding, but this research suggest that learners cannot easily use it to explain other classes of bonding. Therefore for a learner applying the FULL SHELLS EXPLANATORY PRINCIPLE anything that is recognised as bonding may well be classified in terms of the dichotomy ionic-covalent.

§11.6.1: Learner's dichotomies.

It would seem from the research being reported here that typically learners commenced A level with distinct models of covalent and ionic bonding, and criteria to distinguish the two cases. The interview study suggests that the colearners were only likely to have any detailed knowledge of two types of bonding when they enrolled on an A level course (see appendix 37, §A37.1.1), and this is supported by evidence collected from other students setting out on A level chemistry (see appendix 37, §A37.1.2). Some students may well be aware of metallic bonding when they commence their A level studies, but this category does not readily fit with the FULL SHELLS EXPLANATORY PRINCIPLE for explaining bonding (§11.6.6). So in the following classification of bonding, covalent and ionic bonding are explained in terms of the familiar notions of electron sharing, electron transfer and stable electron shells, whilst the metallic bond is just explained as a tautology,

> "The types of bonding are:
> • IONIC; the donation of electrons. e.g. If one atom has one electron in its outer shell, and another has 7, the first atom may *donate an electron* to the second in order for both of them to become stable.
> • COVALENT; is the *sharing of electrons* in order for atoms to become stable. e.g. 2 atoms with 7 electrons in their outer shells each, may each share one electron from another in order to become chemically stable
> • METALLIC; atoms in metals bond tightly together to form a strong substance"
> (Induction exercise, September 1995.)

It would seem from the data collected that it is common for students commencing A level to classify bonds into two categories, using simple criteria:

covalent	ionic
electrons are shared	electrons are transferred
between non-metal atoms	from metal to non-metal atoms

As with all aspects of this study the data collected from the individual colearners reflected their unique cognitive structures. Paminder used the dichotomy covalent-ionic near the beginning of her course, but she did not seem to have *explicit* criteria (such as whether the elements involved were metal or non-metals) for determining bond type. Although Paminder would assign bonds to one of the two categories, it was not possible to elicit her criteria, although *she* seemed to feel the classifications were not arbitrary (see appendix 37, §A37.1.3).

Carol also used the covalent-ionic dichotomy to classify bonds, but whereas for most of the colearners discussed above these two categories were of equal standing, Carol construed ionic bonds to be in some way a lesser category (see appendix 37, §A37.1.4). Indeed in order to interpret her comments coherently it became necessary to conjecture that Carol used the word 'bond' in two distinct ways, to stand for a covalent - and one might almost say a 'proper' to her mind - bond, or for just an attractive force.

The tendency of learners to distinguish between chemical bonds and *just forces* will be considered later in the chapter (§11.7), but Carol was unusual in seeming to class ionic bonds as *just forces*. However, if Carol did not tend to ascribe ionic bonds the same full bond status as covalent bonds, she still gave ionic bonds a higher status than other forms of bonding (see appendix 37, §A37.1.5).

§11.6.2: Learners' classification of polar bonds.

> "well, ionic I suppose. Well, no, covalent I think"
>
> Carol's classification of the polar bond in hydrogen fluoride (C2.432).

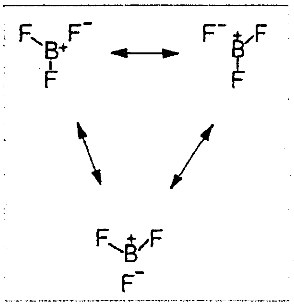
In general then, when learners commence an A level course they have two categories of bond, covalent and ionic, which are distinguished by such criteria as overlap being represented, or the classification of the elements involved as metals and non-metals. These two categories may be explained in terms of the FULL SHELLS EXPLANATORY PRINCIPLE, and may be described by most learners as *sharing of electrons* and *transfer of electrons* respectively. Early in the A level chemistry course students will be taught about the electronegativity scale (in place of the simple metal/non-metal classification), and that most bonds show some degree of polarity rather than being simply covalent *or* ionic.

As would be expected, *before* learners had the category of polar bond available, they tended to classify polar bonds as covalent or ionic (see appendix 38, §A38.1.1).

Interestingly alternative figures representing hydrogen chloride molecules were construed differently by Kabul when he undertook the construct repertory test (November 1992). One triad element was construed as having covalent bonding, and not being an ionic compound, where the other representation of the same molecule was construed as being an ionic compound, and not having covalent bonding (see appendix 38, §A38.1.2).

In the interviews the assignment of a bond as covalent or ionic was sometimes tested by asking the colearner to then compare bonds: asking if two bonds that had both been classed as, say, covalent (when one might be more precisely described as polar) were the same type of bond. When this technique was undertaken with Kabul (in relation to a species where he had described carbon-carbon, carbon-hydrogen and *carbon-oxygen* bonds as covalent), it did not seem to have occurred to him that covalent bonds *could* be different, and he seemed to find the question somewhat meaningless (see appendix 38, §A38.1.3).

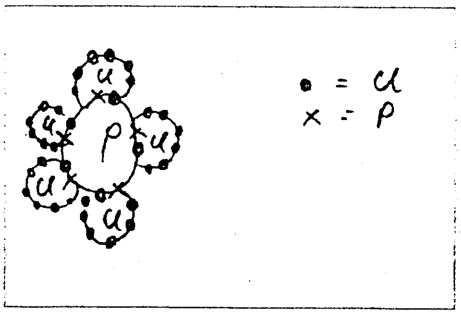
In the present research it was found that there was a strong tendency for learners to often ignore the category of polar bond, and to continue to divide bonds into *covalent* and *ionic*. There are many examples in the data collected of colearners *who had been taught about electronegativity and polar bonding*, labelling a bond as *covalent* or *ionic*, when from the curriculum science perspective it would be appropriate to use the category of *polar* (see appendix 38, §A38.1.4).



focal figure 14

Boron fluoride is an example of a substance where bonding would be expected to be polar according to CURRICULUM SCIENCE Focal figure 14 represented a molecule of boron trifluoride as a resonance between canonical forms (where the individual bonds were shown as covalent or ionic in the individual canonical forms, but where the resonance implies the actual bonds are intermediate). Some of the colearners still used a dichotomous classification, suggesting that there were covalent *and* ionic bonds between boron and hydrogen in the same species (see appendix 38, §A38.1.5).

In the 1994 College mock A level examinations, 31 students answered a question about bonding. When asked to explain the bonding in phosphorus (V) chloride, there were 7 (23%) references to the ionic bonding in the solid state. The phosphorus-chlorine bonds in the molecule (in the vapour phase, or in the $[PCl_4]^+$ and $[PCl_6]^-$ ions in the solid) are polar, but *not one of the candidates mentioned this.* 25 (81%) referred to covalent bonds. Where more details of this 'covalent' bonding was given, 10 students (32% of those answering the question) specifically referred to electrons being 'shared', i.e. the FULL SHELL EXPLANATORY PRINCIPLE description of the bond. (Two students referred to stable electronic configurations, and two mentioned the 'expanded octet'. Only one student mentioned the electrostatic nucleus-electron interaction. There were no references to molecular orbitals.) The following example is from a student who illustrated the type of bonding construed in PCl_5:



"Phosphorus (V) chloride is covalent bonding, in which one electron is supplied by each atom."
(Mock examination response, March 1994.)

So even in an examination context it would seem learners do not tend to readily bring to mind the category of polar bonding. However, it might be suggested that learners are applying the covalent-ionic dichotomy as a first approximation to bond type. Indeed it is quite normal (although perhaps not rigorous) in chemistry to refer to the same bond as covalent *or* polar according to the context as seems appropriate (c.f. the discussion of the chemist's toolbox in chapter 1, §1.7.2). We *might* therefore interpret classifications such as those discussed above as meaning that a bond was 'essentially covalent' or 'effectively ionic'. This could explain most of the dichotomous classifications discussed above (although not the assignment of *both* covalent *and* ionic bonding to boron trifluoride). Yet there were occasions during the research where colearners were clearly not sure of the nature of a bond, but would still tend to prefer the covalent-ionic categories, and would not suggest 'polar', or 'something in between' (see appendix 38, §A38.1.6).

It was also found that explicit reference to electronegativity or bond polarity might nonetheless be accompanied by a dichotomous classification of bond type. At the end of Annie's course she thought the bonding in focal figure 8 was probably ionic. Despite discussing there being a "pole" in the "molecule", she thought that a metal and non-metal normally combined that way (see appendix 38, §A38.1.7). So Annie's more established learning appears to take precedence when she has to classify the bond type. The data collected in this research includes a range of other examples of colearners demonstrating they were able to talk of electronegativity differences and polarity in bonds, but then going on to classify polar bonds dichotomously - even when the bond polarity is particularly relevant to the context of the dialogue (see appendix 38, §A38.1.8).

Hydrogen bonding can only occur where the *intra*molecular bond is sufficiently polar. However, it was found that even where colearners explicitly recognised the presence of hydrogen bonding, and explained that this *implied* a bond between hydrogen and a more electronegative element, they might still label the intramolecular bond as covalent (see appendix 38, §A38.1.9).

One of the consequences of polar bonding is the possibility that bond fission may be heterolytic rather than homolytic (although this is not consistent with a view that on bond fission each atom 'gets its own electrons back', as discussed earlier, §11.4.1). When this possibility was put to Kabul it seemed to be so counter-intuitive that he was nonplused (see appendix 38, §A38.1.10).

It is of interest that the tendency to label bonds as covalent and ionic can co-exist with an ability to explain how the nature of a bond depends on the difference in electronegativity. So a student may classify a bond in a way inconsistent with their own explanation of how they classify bonds (see appendix 38, §A38.1.11).

Where the concept of bond polarity *is* used in classifying a bond, it may be used as a moderator to the primary classes of covalent and ionic. So for Debra the polarity of the bond was a secondary effect, which moderated the covalent bond (see appendix 38, §A38.1.12). Similarly during his course Kabul described polar bonds as *similar to* and *like* covalent bonds, and suggested that polar bonds was a sub-class of covalent bonds (see appendix 38, §A38.1.13). In the same way when Tajinder started to use the descriptor 'polar' for bonds, this did *not* mean he no longer classed them as covalent (see appendix 38, §A38.1.14). There was evidence in the study that other colearners also used the 'polar' label less as a category in its own right, but more as a moderator for the covalent and ionic categories (see appendix 38, §A38.1.15), including Carol who seemed to conceptualise polar bonds as covalent but "*trying* to be ionic" or "ionic but *trying* to be covalent" (c.f.§11.3).

§11.6.3: Learners' classification of dative bonds.

> Dative bonding is:
>
> "When an atom donates both electrons to a *covalent* bond"
>
> (Concept map, first year student, June 1994.)

Dative bonds involve the interaction between a poorly shielded positive core on one species, and electron density - often a non-bonded ('lone') pair of electrons - on another. In an example such as the aluminium chloride dimer, the electrons in the dative bond bridge between species of different electronegativity: in this example the chlorine core has a +7 charge and the aluminium a +3 charge, so the electron density will be greater near the ('donor') chlorine end of the bond. This dative bond is a polar bond.

However in this research it was found that dative bonds were often considered by colearners to be *covalent* rather than *polar*. This is considered to be significant, as from an electrostatic viewpoint the dative bond is clearly polar. However, the covalent category follows from the FULL SHELLS EXPLANATORY PRINCIPLE description of electron sharing, where polar bonding does not readily make sense from such a perspective.

Sometimes in the interviews the colearners simply described dative bonds as covalent (see appendix 38, §A38.2.1). On other occasions dative bonds were presented as ***similar to*** covalent bonds (see appendix 38, §A38.2.2). In Kabul's explanation of the dative bond in aluminium chloride he refers to what he calls the "G.C.S.E. format", which says that "in order to attain a stable state you must have eight electrons", and suggests that "one of the chlorine atoms seems to donate two electrons, and form a dative bond, which is *just similar to covalent bond once it's formed*" (K4.B414). This comment could reflect something that has been emphasised by a teacher or text - that is that it does not matter where the electrons came from, their origin does not effect the bond. This would be a useful teaching point in terms of the 'history conjecture' (§11.4), but if it is put in terms of 'the *dative* bond being like any other *covalent* bond' it may lead to an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5) by encouraging the dichotomous classification of bonds.

Another variant for describing the dative bond was to construe it as *a type of* covalent bond (see appendix 38, §A38.2.3). It would seem that there is little substantial difference between learners seeing a dative bond *as* covalent, as a *type* of covalent bond, or *like* covalent. Whichever of these descriptions is used, the inherent polar nature of the dative bond is ignored. From the CURRICULUM SCIENCE perspective, the dative bond is a special case of the polar bond, and colearners' dichotomous classification of dative bonds is a special case of the tendency for polar bonds to be seen as either covalent or ionic, or as slight modifications of these archetypes.

§11.6.4: Learners' classification of metallic bonds.

> "suppose you have, say for example, sodium, right? Sodium's like made up, suppose you have metal, a sheet of sodium metal, yeah, that consists of metallic bonding, that means like it's made of, like, the metal sodium, and it's just like bonded like between itself, ***it's not ionic, and it's not covalent either, it's like, it's hard to explain this.*** It's just like that metal's bonding there, I mean you don't have something like chlorine mixed with it, and, do you get me? {laughs}"
> Paminder 'explaining' the metallic bond, P2.A195.

The FULL SHELLS EXPLANATORY PRINCIPLE can not be used to explain the metallic bond in terms of a simple pithy description such as sharing or transferring electrons (as in the covalent and ionic cases respectively). In the present study it was found that colearners generally did not know about metallic bonding when they started their course, and any previous learning exhibited tended to be at the level of 'metallic bonding occurs in metals'. Appropriate progression during an A level course would lead to an understanding of metallic bonding in terms of electrostatic interactions between atomic cores and delocalised electrons, and of overlap of atomic orbitals to give molecular orbitals. Data collected during the research suggest that prior to demonstrating this level of understanding colearners' explanations of metallic bonding tended to fall into four general categories:

- there is no bonding in metals;
- there is some form of bonding in metals, but not proper bonding;
- metals have covalent and/or ionic bonding;
- metals have metallic bonding, which is a sea of electrons.

Some of the colearners displayed several of these interpretations at various stages in their course. For example each of these positions, and others, were elicited from Annie as she attempted to make sense of metallic bonding (see appendix 39, §A39.1.1).

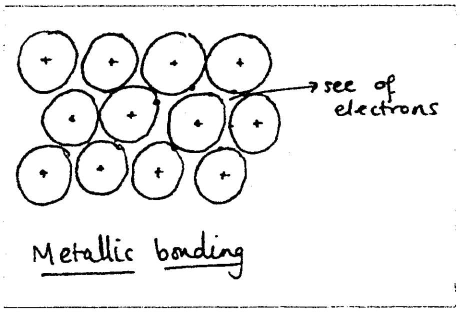
From a CURRICULUM SCIENCE perspective Annie's first suggestion that metals did not have any bonding seems inconsistent with the obvious structural integrity of common and familiar metals such as iron and copper. However Annie felt bonding was not needed, and similar ideas were elicited from Jagdish and Noor (see appendix 39, §A39.1.2). Noordid not think the bonding in a metal was covalent or ionic, and she did not know of any other class of chemical bond. So although she thought there had to be something holding the metal together, she concluded it could not be chemical bonding.

The apparent (i.e. from the octet perspective) paradox that metals held together, but chemical bonds were either covalent or ionic, led to colearners either making apparently arbitrary decisions that the bonding would be covalent (Carol, Kabul, Mike) or ionic (Paminder) or - when colearners had some knowledge of the delocalised electrons and the cations - attempts to rationalise how the bonding was *like* covalent (Kabul), or *like* ionic (Edward), or some combination of the two (Debra), (see appendix 39, §A39.1.3). This tendency was reflected in some of the incidental data collected from other chemistry students (see appendix 39, §A39.1.4).

As colearners progressed through their A level course they became more familiar with the notion of the metallic bond, but there was considerable evidence that incorporating CURRICULUM SCIENCE models of this type of bond into cognitive structure could be a slow process. One colearner (Carol) was reluctant to admit a discrete metallic category of bond, even when she (a) recognised the need for bonding in metals, (b) was familiar with the term 'metallic bonding', and (c) identified it as positive ions in a sea of electrons (see appendix 39, §A39.1.5).

Another colearner, Kabul, actually seemed to 'coin' the term 'metallic bonding' spontaneously before he had formalbeen introduced to it. When he then read up on the topic he learnt that "iron forms a hexagon around it's shell" (i.e. that it was hexagonal close packed), which he interpreted as "it has got six electrons in its outermost [sic] shell" which were bonded to surrounding iron atoms. Based on this he went on to hypothesise that other metals would form different shapes such as decagons, pentagons and triangles (see appendix 39, §A39.1.6). This finding was idiosyncratic, but is interesting for two reasons. Firstly, Kabul built an alternative model of metal structures based on something he had read in a textbook, and his knowledge of the 'hexagonal' structure of iron could be considered as acting as an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5). Secondly, the assumption that the number of bonds equated with the number of valence shell electrons - in principle at least, actually Kabul misidentified which electrons were in the outer shell - is very similar to the VALENCY CONJECTURE commonly found with ionic bonding (§11.5). That is a notion of valency from covalent bonding was misapplied in a context where it was not valid.

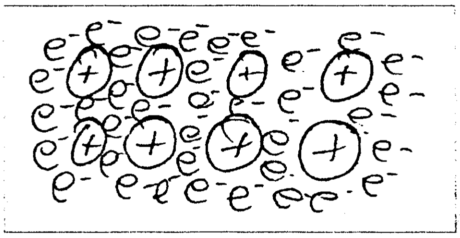
Although colearners readily took up the idea of a *sea of electrons*, there was evidence that this was sometimes little more that rote learning of a new expression. For example, in Lovesh's first term he drew the types of chemical bond he was aware of. His diagram of metallic bonding gave little clue about the nature of the bonding, beyond the labelling of an interstitial space as "see [sic] of electrons".



Lovesh's diagram for metallic bonding, November 1992

Umar was actually familiar with the term 'sea of electrons' from his school course. Despite this when he was probed he described covalent and ionic bonds in pure metals and alloys respectively (see appendix 39, §A39.1.7). Other colearners also had difficulty making sense of the *sea of electrons* model , and some extended the *sea* metaphor to have the conduction electrons *swim* or *floating about* in the sea (see appendix 39, §A39.1.8).

In the 1994 College mock A level examination, of the 31 students answering the question on bonding, 23 (74%) referred to metallic bonding when explaining the bonding in copper, and an equal number mentioned the *sea of electrons.* Some students referred to the *sea of electrons* without giving any clear indication of what this metaphor is meant to imply, being satisfied to provide simple descriptions (see appendix 39, §A39.1.9). Certainly several of the students' diagrams of metallic bonding in copper seemed to show an imbalance of charge (see appendix 39, §A39.1.10), such as the following example:



"Copper. This has mettalic [sic] bonding. In Mettalic bonding the atoms are held together in a "sea" of electrons which acts like a glue."
(Mock examination response, March 1994.)

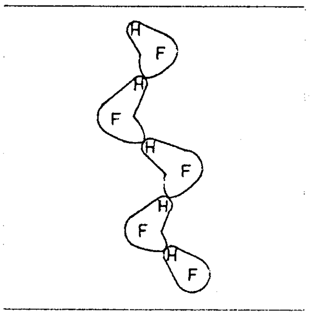
Two of the students taking the examination extended the *sea* metaphor to suggest that the cations were *like islands* in the sea, and there were also references to the electrons *drifting*, and to the cations being *suspended* and *floating* in the sea (see appendix 39, §A39.1.11).

In the interview study there was some suggestion that the *sea of electrons* description of the metallic bond - although limited in itself - could act as a suitable image for developing an electrostatic model of the bond. However, the evidence from the mock examination presented above suggests that even if these A level examination candidates had acquired an electrostatic model of the bond, a significant number were content to give examination responses in terms of the *sea* image alone. This is an issue that will be considered in my final chapter (§12.4.3). The following proposition from a concept map (drawn up as an end-of-first-year revision exercise) suggests that even when an electrostatic model of the bond is taken up, this may supplement - rather than develop - the *sea* metaphor,

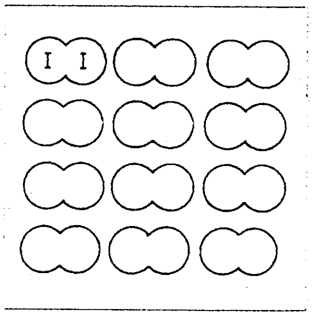
> "Metallic bonding is only occrent [sic] in metals and is the attraction between the +ve charge of the metal ions and the -ve charge of the electrons. It *also* has a sea of electrons which flow around the structure."
> (Concept map, first year student, June 1994.)

§11.6.5: Learners' classifications of intermolecular bonds.

If learners commence A level with a bonding typology limited to covalent-ionic, then they do not have appropriate categories to deal with inter-molecular bonds.



focal figure 11



focal figure 17

One response to being shown diagrams such as focal figures 11 and 17 was to deny that there was any intermolecular bonding present in the substances represented (see appendix 39, §A39.2.1). Where the colearner recognised that something must be holding the molecules together, this would be considered as an attraction or force, but not a chemical bond (see §11.7).

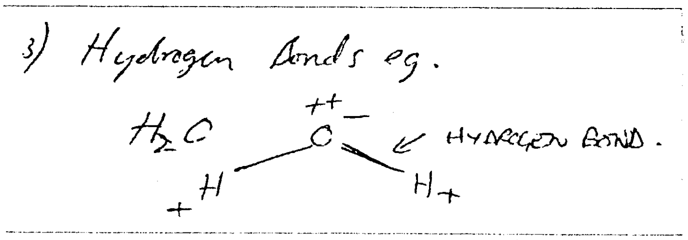
However, sometimes colearners did identify intermolecular bonding, but - as with the metallic case above - in terms of the familiar categories of covalent and ionic bonding (see appendix 39, §A39.2.2).

Although colearners were generally unaware of hydrogen bonding at the start of their A level courses, there were a number of examples in the interviews of the ***term*** 'hydrogen bond' having been acquired, without an appreciation of the intended meaning (see appendix 39, §A39.2.3). In her second interview Debra suggested that the ***intramolecular bonding*** in hydrogen fluoride was hydrogen bonding (D2.343). Similarly, Paminder's construed diagrams representing methane or hydrogen as containing hydrogen bonds. After some questioning it was found that for Paminder hydrogen bonding was where hydrogen was bonding to something: "because, if you think about it, you know, 'hydrogen bonding', that's like, you know, 'what is *hydrogen bonding* to?' It's kind of that sense" (P2.A309). Paminder had apparently met the term hydrogen bond in the context of D.N.A. in biology, and seemed to have just adopted what seemed a likely meaning, i.e. a bond to hydrogen. It seems that references in her biology lessons had led to an EPISTEMOLOGICAL LEARNING IMPEDIMENT. Similarly, Umar seemed to have made the same 'intelligent guess' at what was meant by the term: "if 7's bonded to another atom" (U2.B034).

The meanings adopted by colearners Debra, Paminder and Umar were reflected in two responses to induction exercises taken by students commencing A level studies. One student defined the hydrogen bond as if it was a covalent bond involving hydrogen,

> "Hydrogen bond is when a hydrogen shares the same electrons with another element"
> (Induction exercise, September 1995.)

Another drew a diagram of the 'hydrogen bond', within what was apparently a water molecule,



Induction exercise, September 1995

It would seem that possible consequences of learners commencing A level with a limited typology of chemical bonds include,

- not recognising the presence of intermolecular bonding;
- classifying intermolecular bonds as ionic or covalent;
- interpreting the term 'hydrogen bond' within the covalent-ionic classification, as a type of covalent bond that involves hydrogen.

§11.7: The 'just forces' conjecture: distinguishing between bonds, and 'just forces'.

It was shown above that intermolecular bonds may be misclassified as ionic or covalent by some learners (see appendix 39, §A39.2.2). Carol, Debra and Paminder all proposed ionic bonds in contexts where there were no ions shown. Kabul suggested extended covalent bonding in iodine without consideration of valency restrictions. These misclassifications may be seen as an attempt to categorise examples of bonding a learner meets, within a limited typology. An alternative strategy would be to discount phenomena that do not fit the covalent-ionic scheme as something other than bonding.

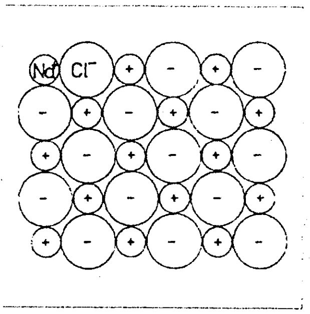
Some forms of interaction that are accepted as examples of chemical bonding within CURRICULUM SCIENCE may be labelled as 'just forces' by a student who understands bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE. For example interactions such as hydrogen bonding that do not lead to new octet configurations may not be considered to qualify as bonds. When considering ionic materials, application of the VALENCY CONJECTURE may limit the number of bonds an ion is seen to form, and application of the HISTORY CONJECTURE will allow a specific interaction to be identified as the ionic bond. The other interactions between counter ions may be considered to be *just forces*.

§11.7.1: Ionic bonds as just forces.

As reported above (§11.5), it was found that at the start of their A level course the colearners interviewed tended to suggest that in an ionic structure, such as sodium chloride, the number of bonds an ion could form was limited by its valency: so for example a sodium ion could only be bonded to *one* chloride ion. The colearners usually recognised that other ions would also adhere, but this was not considered to count as bonding. Rather the other ion-ion interactions were attractions, or forces (see appendix 40, §A40.1.1). Sometimes it was claimed that the interactions that were just forces were weaker than the force due to the ionic bond: so for example, Kabul distinguishes 'strong attractions' where electron transfer has taken place with 'weak attractions' with the other ions, and for Paminder an ion is most strongly attracted to "the one it forms a bond with", because "that's where it's transferred the electrons".

Similar views to those elicited from these colearners have been expressed in responses to course tests undertaken by other A level students (see appendix 40, §A40.1.2).

Appendix 2 describes a simple pen-and-paper instrument (the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT) used in the research to test whether some aspects of colearners' thinking elicited in this study were more widespread. One of the aspects investigated was the notion that in an ionic material the interactions between counter ions that had not exchanged electrons were not bonds, but rather just forces: the JUST FORCES CONJECTURE. The instrument was used to test a sample of 81 A level students who had not yet studied bonding at that level, and 128 who had (see appendix 2 for details). Five of the thirty items in this instrument related to the application of the JUST FORCES CONJECTURE to focal figure 5.



focal figure 5

The five items were:

6. In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.
9. A positive ion will be bonded to any neighbouring negative ions.
22. In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.
25. A negative ion will be bonded to any neighbouring positive ions.
26. There are exactly fifteen ionic bonds in the diagram.

From a CURRICULUM SCIENCE perspective the two statements that *a positive ion will be bonded to any neighbouring negative ions*, and *a negative ion will be bonded to any neighbouring positive ions* are clearly correct, yet these propositions were thought to be false by 32% and 32.5% respectively of those A level students who had yet to study bonding. The statements were judged to be false by 27% and 30% respectively of the students who *had* studied bonding as an A level topic.

The most explicit statements of the JUST FORCES CONJECTURE were supported by a considerable proportion of the students responding to the instrument. The statement that *in the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces* was judged 'true' by 41% of the A level students who had not yet studied bonding as an A level topic, and 35% of those who had. The complementary statement that *in the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces* received even stronger support, with 53% and 45% selecting 'true' of the A level students who had not yet studied bonding as an A level topic, and of those who had, respectively.

Focal figure 5 shows 30 ions, which from the FULL SHELL EXPLANATORY PRINCIPLE would be perceived as fifteen bonded ion-pairs. The consequent statement that *there are exactly fifteen ionic bonds in the diagram* was thought to be true by 44% and 30% of the A level students who had not yet studied bonding as an A level topic, and of those who had, respectively. (If an ionic bond is taken as a bond between two adjacent oppositely charged ions, then focal figure 5 actually features 49 ionic bonds.)

It would seem then that, on the basis of the evidence presented, the notion of two types of attractive interactions in an ionic lattice, i.e. ionic bonds and just forces, may be widespread amongst A level chemistry students, even though it is not sensible from a CURRICULUM SCIENCE perspective.

At certain points during the research interviews, the ionic category of bond was itself excluded from chemical bonding by some colearners. In some cases, such as Kabul and Lovesh, this seems to be an alternative position taken up when the colearner was no longer able to accept the JUST FORCES CONJECTURE. However, in some cases this view was adopted early in the interviews, rather than as a 'fall-back' position (see appendix 40, §A40.1.3). So for Annie at the start of her course, bonding was represented by "circles that overlap" and Annie did not think there was bonding in focal figure 5 where "they don't actually overlap or anything", rather "it would probably get held together by *just forces*". At one stage in her course Carol suggested ions would "*not bond*, but go together 'cause they're opposite charges". Kabul passed through a similar phase when he apparently did not construe the tenuous ionic bond, that was "between everywhere", as being *as much of a bond* as the covalent bond where there was "electron sharing" (these and other examples are discussed in the appendix).

§11.7.2: Metallic bonds as just forces.

> "The metallic bond is the bond formed between metal ions themselves. Metal atoms, sometimes have free electrons in their conduction bands that are free and have enough energy to leave the metal atoms. These leave the metal atoms, i.e. they become ions. These ions, are then positively charged, because they have lost electrons. Therefore the positively charged ions, are attracted to the electrons, therefore the metal forms this kind of lattice solid, with their own electrons that they have lost. This is called the metallic bond. Ionic and covalent bonds, are formed with other atoms or groups of different atoms, where atoms lose or gain electrons, or share them, where as [sic] *metallic bonding is not the sharing or loss or gain of electrons*. It is *just a lose association* with metal ions, and electrons they have lost, where this helps to hold the solid metal lattice together."
>
> (Colearner Quorat: Test response, December 1992.)

Earlier in this chapter it was suggested that some colearners were unable to understand metallic bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE (§11.2.3), and dealt with this by various strategies. One approach was to consider that metals did not contain bonds as such, but *just forces* holding them together (see appendix 40, §A40.2.1), and in Noor's case this was judged to be a very weak attraction.

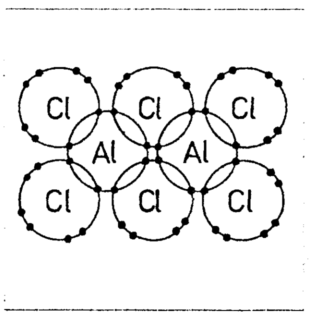
At the start of her course Jagdish did not think there was any *bonding* in iron, although the atoms "do stick together", so "there must be" *force* between the iron atoms. Jagdish looked the topic up in her texts, but considered the books unhelpful.

Jagdish appeared to have some form of 'mental block' over the idea of bonding in a metal. She reported that if two different metals were melted down, mixed and left to solidify, she thought that metallic bonding would form, and she felt she understood that. She also thought it must be "the same thing if I just had like two different containers of iron and melted together, and put them together into one container": but despite this she could not understand "what bonding is holding the iron atoms together". Jagdish referred to molecules in the metal to explain what was happening, but this seemed to be a purely heuristic device ("helpful when you ... talk about, *what are bondings* inside the iron that are holding it together, but not [when you are asked] *what is an iron molecule?*").

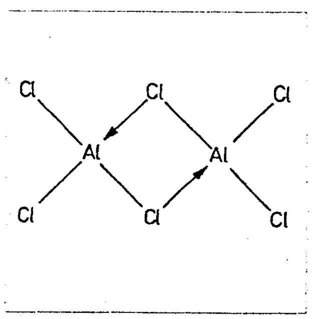
§11.7.3: Polar bonds as just forces.

Another category of bond that some colearners had difficulty in explaining in terms of the FULL SHELLS EXPLANATORY PRINCIPLE was the polar bond. Although this was often simply considered to be covalent, or ionic, or some modification of one of these types (see §11.6.2), there were examples of colearners excluding polar bonds from full bonding status (see appendix 40, §A40.3.1). So for Carol the interactions in a hydrogen fluoride molecule were not covalent or ionic, but rather "something to do with electronegativity".

§11.7.4: Dative bonds as just forces.



focal figure 15



focal figure 16

A particular type of polar bond which some colearners found difficult to classify was the dative bond (as discussed earlier in this chapter, §11.2.4, §11.6.3). In Quorat's first interview for the research she described focal figure 16 as "aluminium chloride" with "six covalent bonds" and "*just attraction*" (Q1.B412). In Tajinder's first interview he dismissed focal figure 15 as "wrong" because it showed chlorine with two bonds and aluminium with four (T1.C119). However he accepted focal figure 16, which he also interpreted as having "six" "covalent" bonds. He thought the the arrows were meant to represent the "force of attraction", rather than a bond (T1.C134).

§11.7.5: Hydrogen bonds as just forces.

Hydrogen bonding, unlike polar and dative bonds, can not be construed in terms of forming full shells, and thus was prone to be being excluded as a type of bonding by colearners operating from that criterion (see appendix 40, §A40.4.1). So hydrogen bonding was described as a type of "intermolecular force" (Jagdish), or "intermolecular attraction" (Lovesh); and, as Tajinder suggested, the hydrogen bond is "*not actually a bond*, but it's a force".

§11.7.6: Solvent-solute bonds as just forces.

The interactions between solute and solvent molecules in a solution are important, as unless they are large enough solvation will not occur (as the energy has to be provided to overcome interactions between the solute ions/molecules for example). Deviations from Raoult's law are often explained in terms of the relative strengths of the bonds between the various species present, where it is assumed that the interaction between solvent and solute particles is a type of bond. However, these types of interaction are not explained by the FULL SHELLS EXPLANATORY PRINCIPLE, and are not 'bonds' from such a criterion.

In the present research it was found that colearners would not consider these types of interactions as bonds, rather they were just an attraction (see appendix 40, §A40.5.1).

§11.7.7: Van der Waals bonds as just forces.

> "they're just forces aren't they?"
> Carol at the end of her course (C3.4).
>
> "it's actually a type of force, *it's not actually a chemical bonding*"
> Tajinder (T8.A289).

Like hydrogen bonds, van der Waals forces do not involve the formation of octets, and thus may not be considered as bonds where learners define bonds in terms of the FULL SHELLS EXPLANATORY PRINCIPLE. So in a molecular solid the molecules are not held together by chemical bonds but by just the forces (see appendix 40, §A40.6.1). As Annie said at the end of her course, "it's ***not bonding***. But there's sort of van der Waals' forces", and Tajinder thought it was "not actually bonding" rather "the positive-negative attraction". Kabul also made the distinction between forces and bonds when he explained that van der Waals' forces were "neither ionic, or covalent, you know. *Just an attraction and repulsion* between atoms." He thought that solids held together by these van der Waals' forces had low melting temperatures "because there are weak forces (***no bonds***) between individual molecules".

So at various times during the interviews undertaken for this research colearners excluded the following types of interaction from being chemical bonds:

- ionic bonds - either in total, or those not seen as due to electron transfer;
- polar bonds, including dative bonds;

- metallic bonds;
- hydrogen bonds and other types of permanent dipole-dipole and ion-dipole interactions;
- van der Waals forces.

In each case the type of interaction concerned was recognised as a force between different atomic or molecular species, but as *just forces*, not chemical bonding. In most of these cases this classification may be interpreted as a consequence of defining chemical bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE, and being unable to construe the interactions as bonds by this criterion.

Chapter 12.

Discussion.

§12.0: Overview of this chapter.

In this final chapter I intend to draw together the major themes of this thesis. In particular I will summarise what I have learnt about the developing understanding of chemical bonding among A level students, and consider the implications of my study.

The chapter commences with a brief overview of my findings and the identification of the key feature of students' developing understanding of the chemical bond (§12.1). The major LEARNING IMPEDIMENTS that have been uncovered in this research are reviewed (§12.2). It is then argued that one of these impediments, students' use of *octet thinking*, should be ascribed the status of an *alternative conceptual framework* that represents common aspects of student thinking (§12.3). Student progression in the topic is then considered in terms of models of the understanding of a typical [sic] A level 'fresher'; the 'ideal' A level examination candidate; and the two colearners Annie and Tajinder at the time they sat their A level examinations (§12.4.1). This provides the basis for considering a question introduced in chapter 1 (§1.7.5): whether students' alternative conceptions should be considered as metaphorical *barriers* or *bridges* in the learning process (§12.4.2); and in particular whether *octet thinking* is a 'stepping stone' on an appropriate conceptual trajectory (§12.4.3). One aspect of *octet thinking*, anthropomorphic language, is considered to have a potential role as a mediator between the highly abstract and the familiar (§12.4.4). Then, in view of the difficulty learners have passing beyond *octet thinking*, an alternative conceptual trajectory to understanding chemical bonding is considered (§12.4.5). I then turn to consider what others can learn from this research. I offer advice to teachers and those responsible for the curriculum, based on my consideration of the learning impediments discussed in this thesis (§12.5). I also provide a list of potentially fruitful avenues of further research that follow from work reported (§12.6). Finally, on a personal note, I explain the most important lesson I have drawn from this study.

§12.1: Understanding chemical bonding.

In this thesis I have suggested that an understanding of chemical bonding at the level of G.C.E. Advanced level (A level) syllabuses requires the acquisition and use of conceptual tools based upon Coulombic and quantum principles. The 'A level chemist' would not be expected to develop a full appreciation of quantum mechanics, but certain key orbital ideas are important at this level (see appendices 4 and 6). Electrostatic (Coulombic) ideas are part of the assumed background knowledge widely applied in explaining facets of chemistry at this level (see chapter 3 and appendix 5).

It is widely accepted that quantum ideas are non-intuitive (§9.1), and there was much evidence that some orbital ideas were difficult to learn (see chapter 9), for example distinguishing between *orbitals* and *energy levels*, and the three-fold distinction between *ground state atomic orbitals*, *rehybridized atomic orbitals* and *molecular orbitals*. However, besides making a transition from thinking in terms of shells to orbitals, and perhaps learning to ignore the normal meaning for 'spin', the orbital ideas these learners met could largely be classed as a novel conceptual domain, and not replacements for specific existing conceptions. Therefore the main barrier to acquiring these ideas was their abstract and complex nature, rather than strongly held contradictory notions. In terms of the typology suggested in chapter 1 (§1.5), students may experience a DEFICIENCY LEARNING IMPEDIMENT because they do not have any direct experience of the quantum world.

Whereas A level chemistry students would not be expected to have any knowledge of orbitals at the beginning of their course - and indeed this was generally true for the colearners in the present project - some basic electrostatic ideas would be an expected prerequisite for A level chemistry (appendix 5). All the colearners in the study had *some* notions of electrostatic interactions when they were first interviewed, although these were not necessarily seen to be relevant to chemical bonding. Indeed the development of an electrostatic conceptual framework for chemical bonding was generally impeded by two types of SUBSTANTIVE LEARNING IMPEDIMENTS (§1.5.3). The first was the nature of the colearners' existing conceptions of electrostatics (see chapter 10), and the second was the existence of an alternative explanatory principle for explaining chemical bonds (see chapter 11). The former conceptions were largely consistent with those previously reported in the literature (§3.1.3), and which are often considered as 'intuitive theories' or preconceptions. In my typology they would be best labelled as ONTOLOGICAL LEARNING IMPEDIMENTS (§1.5.4). In contrast, the common use of a FULL SHELLS EXPLANATORY PRINCIPLE (§11.2) was 'alternative' to an acceptable understanding of chemistry at A level, but was based on *taught* rather than intuitive ideas. Thus, the presence of this principle in a learner's cognitive structure may be considered to be an EPISTEMOLOGICAL LEARNING IMPEDIMENT (§1.5.5), and may suggest that the teaching of some aspects of chemistry in schools needs to be rethought. Although not all the colearners held exactly the same set of ideas, the evidence from this study is that the presence of *an explanatory principle based on the octet rule* may be very common among chemistry students commencing A level (§11.2). I have presented a model of the way such an explanatory principle based on the octet rule may become the basis for a range of common features in learners utterances and written statements. These features have been referred to as *octet thinking* (chapter 11).

It is argued here, based on the analysis presented earlier, that:

> **the major theme for progression in understanding chemical bonding during an A level course may be characterised as the construction of an explanatory scheme based on electrostatic principles.**

§12.2: Learning impediments to progression in understanding chemical bonding.

The main SUBSTANTIVE LEARNING IMPEDIMENTS to developing understanding of chemical bonding revealed in this research related to

(i) learners' alternative notions of forces between charges, and

(ii) the common preexisting rationale for bonding developed from the octet rule heuristic.

§12.2.1: Alternative electrostatics.

Among the alternative conceptions (i.e. conceptions alternative to CURRICULUM SCIENCE) of electrostatics uncovered were:

- alternative ideas about equilibrium and non-equilibrium (§10.3), or NEWTON-1 ERRORS as I have labelled them:
    - if a zero net force is acting on an object, it is stationary (rather than not accelerating), and if an object is moving it must experience a net non-zero force.
    - a stable structure (i.e. configuration of several particles) is held together by a net attractive force (rather than a zero net force).
- alternative ideas about the reciprocal nature of forces between bodies

(§10.4), or NEWTON-3 ERRORS, as I have labelled them:
  - a larger body attracts a smaller body, but the smaller body does not attract the larger body.
  - a larger body attracts a smaller body with a larger force than the smaller body attracts the larger body.
  - if one body attracts a second body, the second body repels the first body.
- a notion that a charge (by itself) gives rise to a set amount of attraction regardless of other charges that it may be interacting with - a conception that I have tagged as CONSERVATION OF FORCE (§10.5).

There was evidence that the *conservation of force* conception was widely used by colearners and so it is considered to have the status of a key ***explanatory principle*** (§10.5.4).

Another alternative conception uncovered was colearner Annie's interpretation of charge symbols ('+', '-') as DEVIATION CHARGES (§7.2.2). This was very significant for ***her*** developing understanding of chemical bonding, but was not found with any of the other colearners.

Newton-1 errors. The literature reviewed in chapter 3 suggested that learners commonly have alternative notions to Newtonian mechanics. According to the CURRICULUM SCIENCE perspective chemical reactions occur - that is chemical bonds break, and other chemical bonds form - as a result of systems of forces that are not in equilibrium; whereas the forces acting in stable structures ***are*** in equilibrium. Although this point is not often explicitly made in the explanations given in textbooks, it is an implicit assumption. A student who does not tend to consistently apply Newton's first law will find some of the arguments used at chemistry at this level nonsensical. The research carried out for this study reflects the literature (§3.1.3) in finding that learners do not always recognise the conditions for equilibrium or non-equilibrium situations (§10.3).

Newton-3 errors. As reported in chapter 3, the literature suggests that Newton's third law is commonly counter-intuitive to learners (§3.1.3). In the present study A level students were found to assume that the larger body must be exerting the larger force (§10.4.4). This assumption was made by students in contexts of everyday phenomena (such as falling apples), astronomical systems (such as earth-moon) ***and*** systems at the molecular level. The finding that learners commonly expected a nucleus to attract an electron more than the electron attracted the nucleus would seem to be a more abstract example of the same principle that leads to their expectation that the earth would pull on an apple more than the apple would pull on the earth.

Conservation of force. The specific finding that chemistry learners in this study commonly held a notion of *conservation of force* (i.e. that a given nuclear charge can - or will - give rise to a set amount of force, to be shared amongst the electrons present), would seem to be an original discovery (§10.5).

However, it is consistent with some of the results of previous workers, as discussed in chapter 3 (§3.1.3). For example, it is known that for some learners the concept of force is not clearly distinguished from momentum or energy, so perhaps a conflation with charge should not be surprising. Possibly even more significant is the way that the literature suggests that learners commonly talk of the force *of a body*, rather than the force between two bodies. Watts' DESIGNATED FORCES framework (1983a) may be particularly important here, as in the present study learners commonly designated forces to nuclei. Perhaps this is an example of the common Gestalt suggested by Anderson, the experiential gestalt of causation (§2.4.4), where the the nucleus was the *agent*, acting on the *object* (an electron) through the *instrument* of *its* force.

§12.2.2: Octet thinking.

The second category of SUBSTANTIAL LEARNING IMPEDIMENT (impeding the colearners from acquiring an effective electrostatic conceptual framework for explaining chemical bonding that largely matched CURRICULUM SCIENCE), was the existence of a range of ideas which I have interpreted as linked through the use of an explanatory principle based on the octet rule (see chapter 11).

The summary of *octet thinking*, as set out below, is not from any one student, but is a model which has some features that match utterances from each of the colearners. Indeed, in terms of this model, some of the colearners would best be considered to have been *in transition* between octet and electrostatic complexes at the start of their A level courses. Nevertheless each of the colearners matched the model in some parts.

The core conceptions are:-

- atoms *want* full outer shells;
- atoms form bonds to obtain full outer shells;
- atoms may form bonds by sharing or transferring electrons;
- a covalent bond is the sharing of electrons;
- shared electrons 'count' (for 'full shell' purposes) towards the shells of both atoms sharing them;
- an ionic bond is the transfer of electrons between atoms;
- atoms are stable if, and only if, they have full outer shells.

Subsidiary conceptions that may also be present are:

- electrons belong to atoms;
- in a covalent bond each of the bonding electrons is more strongly attracted to its own atomic nucleus;
- when a covalent bond breaks the electrons return to their own atoms;
- in an ionic lattice there is a distinction between the interactions between the specific ions which were formed by a particular electron transfer event, and the interactions between other counter-ions;
- in sodium chloride ion-pairs are (or are like) molecules;
- the true structure of sodium chloride contains two distinct adjacent cation-anion separations;
- the species solvated in salt solutions are atoms, as transferred electrons return to their own atoms as the lattice is broken up.

§12.3: An alternative conceptual framework: the octet rule framework.

In chapter 2 I presented a discussion of the terms used in the literature to label learners' ideas elicited in research (§2.4). In particular, the term *conceptual framework* was considered, and it was pointed out that this term was used in different ways by different researchers (§2.4.1).

Some workers have used the term framework to describe the thinking of an *individual* learner, and there has been criticism of (composite) alternative frameworks presented in the literature, as not adequately reflecting to thinking of *specific* learners (§2.4.2). In my results section I have attempted to avoid this potential source of ambiguity by discussing the *explanatory principles* that colearners

Annie and Tajinder appeared to be applying, and how these might lead to *complexes* of ideas.

I propose that - in the sense of one common use of the term - ***octet thinking*** in chemistry represents an ***alternative conceptual framework***. However, this suggestion is indeed open to the criticism that my model of *octet thinking* does not entirely match the thinking of my colearners in all details. I wish to make clear therefore that on the basis of my research I am proposing an alternative conceptual framework in the sense of what I labelled in chapter 2 as ALTERNATIVE FRAMEWORK2 i.e., in Gilbert and Watts' 1983 terms, "thematic interpretations of data, stylised, mild caricatures of the responses".

Features of
the OCTET RULE ALTERNATIVE CONCEPTUAL FRAMEWORK2:

- considering atoms as the basic ontological entities of chemistry, and electrons as parts of (specific) atoms;
- the FULL SHELLS EXPLANATORY PRINCIPLE used as the reason for chemical reaction and bond formation;
- discussing bonding phenomena in anthropomorphic terms, as if atoms were sentient actors;
- imbuing previous states as being significant, in the sense of electrons having 'memories' of their origins, and tendencies to act accordingly;
- construing the ionic bond through a molecular model where the bond is defined in terms of electron transfer, and thus the number of bonds is limited to the electrovalency, giving a molecular entity (whether in name or not);
- bonding is construed in terms of the ionic and covalent models that 'make sense' according to *octet thinking*, so that *bonds* are construed as ionic *or* covalent (e.g. when they would more appropriately described as polar); or as *like* ionic or covalent (e.g. the metallic bond may be seen as like an ionic bond);
- interactions that can not be classed as ionic or covalent are considered *not* to be proper bonds, but *just* forces.

In developing this ALTERNATIVE FRAMEWORK2, I have started from interpretations of the thinking of individuals - and have presented my own interpretations of the complexes (*individual* conceptual frameworks) of Annie and Tajinder: that is their ALTERNATIVE FRAMEWORKS1.

However - although I believe that case studies are of intrinsic interest, and are important in following the progression of student thinking - there is a sense in which they ***may*** be seen to be largely of academic interest. No other chemistry teacher will have Annie or Tajinder in his or her class for A level chemistry, and therefore aspects of my findings which are idiosyncratic to these individuals have limited value in informing the teaching of other practitioners.

For example, Annie's DEVIATION CHARGE conception (§7.2.2) is of interest as an example of how a learner can misinterpret CURRICULUM SCIENCE, yet still manage to build up a scheme for making sense of the subject based on an alternative conception of a fundamental point. It was also of great significance in her own understanding of A level chemistry, and had I interpreted Annie's comments earlier in the study I may have been able to offer a more effective input as a teacher. (Conversely, if Annie had ***not*** been a colearner in my study, then it seems likely she would have passed through the entire course with her alternative conception never diagnosed; and would have had no opportunity for the remedial feedback provided before her examination.)

However, no evidence was found in the study, that Annie's DEVIATION CHARGES had direct parallels in the cognitive structures of other chemistry learners. Probably the ***general*** notion of DEVIATION CHARGES is not ***unique*** to Annie, but it would seem to be a rare alternative conception, and there is little point advising other teachers to be vigilant in spotting it amongst their students.

On the other hand, Tajinder's CONSERVATION OF FORCE EXPLANATORY PRINCIPLE did seem to have close parallels among the thinking of other learners in the study, and my description of this aspect of Tajinder's thinking (§8.2.5) would seem to match a common alternative conception (§10.5). It does seem appropriate to inform other chemistry teachers that some of the students in their classes will be interpreting their teaching about topics such as ionisation energy in terms of notions that are closely described by my model of the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE.

In a similar way, the OCTET RULE FRAMEWORK that I am presenting here is a model that represents aspects of the thinking of the *all* of the colearners interviewed, and was found to be reflected in other data collected from a wider range of chemistry learners. As there is no reason to suspect that the learners concerned are atypical of the wider population of A level chemistry students, the OCTET RULE FRAMEWORK *is* of considerable significance to chemistry teachers. Indeed, as *octet thinking* was shown to be present at the start of an A level course, and to still be in evidence at the end, this is an alternative conceptual framework that has consequences for teachers of school science, A level chemistry, *and* University chemistry.

§12.4: Progression in understanding chemical bonding.

In this research a view of progression in learning chemistry has been taken (§1.7) which has allowed me to accept that learners' cognitive structures may include a range of conceptual tools of varying degrees of coherence which may be used to construct explanations in chemistry which are integrated to varying extents. (This was related to the state of chemistry itself as a discipline - §1.3.1, §1.7.1.)

In the following section I will discuss the progression in understanding chemical bonding that might be expected for an 'ideal' student, and compare this with what was found in the present research. The complexes of ideas about chemical bonding elicited from Annie and Tajinder will be represented diagrammatically in a form similar to Venn diagrams used to show sets. These diagrams (figures 12.4 and 12.5) will emphasis how colearners were found to be able to construct largely distinct complexes of ideas built around alternative explanatory principles, which they used to answer questions about chemical processes. So Tajinder could explain bond formation in terms of minimising energy, forming octets or the action of electrostatic forces. In chapter 2 the phenomenon of 'multiple frameworks' was considered (§2.5.2). Whereas some commentators had dismissed *multiple frameworks* as evidence of researchers attempting to fit learners' ideas to their preconceived and inadequate categories, I suggested that from a Kellyan perspective the possibility of an individual holding several incommensurate versions of a concept area in cognitive structure was quite plausible. The longitudinal nature of my research has demonstrated that Tajinder's alternative explanatory principles for explaining bonding were stable and theory-like, and could not be explained away as *minitheories* (c.f. Claxton, §2.6). Moreover, although I have emphasised the inadequacy of *octet thinking*, Tajinder's OCTET RULE EXPLANATORY PRINCIPLE meets Solomon's criteria of 'scientific knowledge' (table 2.1), and can not be assigned to a distinct 'life-world' system of knowledge (c.f. §2.7). My research suggests that *multiple frameworks* may reflect genuine aspects of learners' cognitive structures, and that - at least in a topic area where CURRICULUM SCIENCE can not offer a single coherent explanatory model (§1.7.1) - learners such as Tajinder can accept this ambiguity without apparent problem (see appendix 29).

§12.4.1: Representing colearner progression in understanding chemical bonding.

In chapter 2, figure 2.3 presented a schematic model of the colearner seen as a system of components (such as perceptual and processing units and aspects of cognitive structure). Figure 12.1 reproduces the main features.

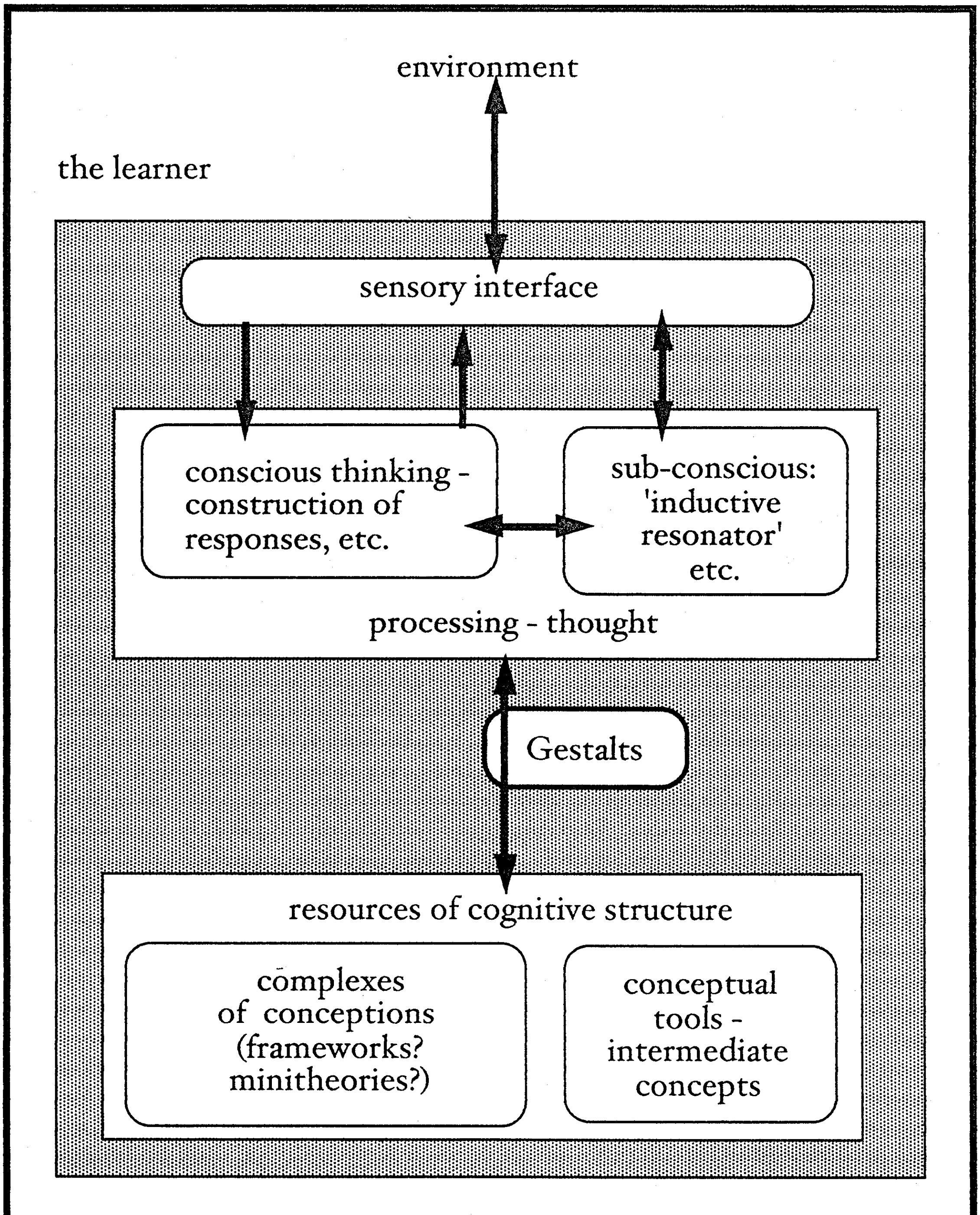


figure 12.1 - the learner

In chapter 1 some basic working assumptions about cognitive structure and the learning process were made (§1.4) - including the notion that it is possible to devise models of a learner's conceptual structure that may be judged by their utility in explaining data.

In figure 12.1 the box labelled 'resources of cognitive structure' is shown as having two types of component - conceptual tools, and complexes. This is a *simplistic* division, and it may well be that there is a continuum of scales within an individual's conceptual structure. It may also be the case that as the complexes *include* the conceptual tools it is an *artificial* distinction. It is beyond the scope of this study to attempt to determine whether this is the case, but the arguments concerning conceptual change discussed in chapter 2 (§2.10) suggest that several frameworks may exist in parallel that include 'the same' concepts. The model that has been adopted assumes that cognitive structure may be treated *as if* it contains concepts that may be used as components in constructing arguments (and building higher order concepts); and also complexes of conceptions that incorporate (copies of) those concepts.

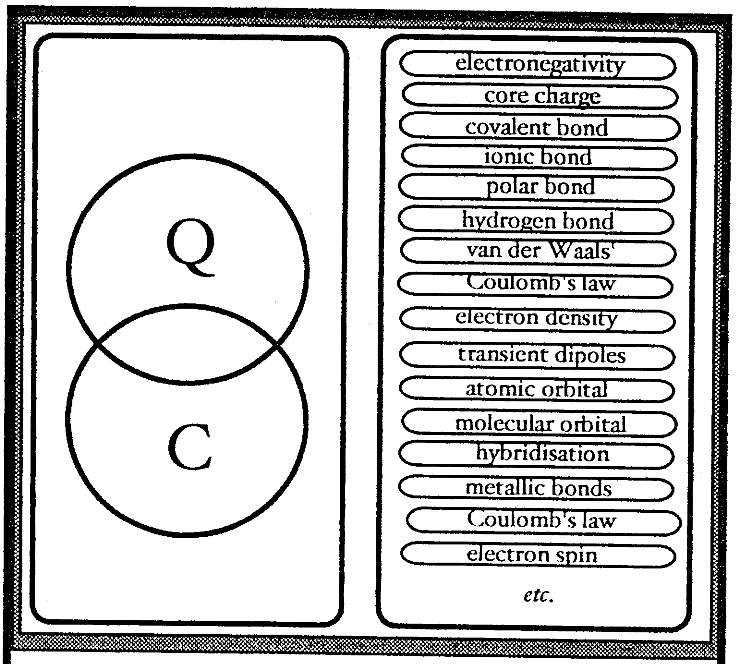


fig.12.2 - cognitive resources of an ideal A level candidate

In terms of such a model it is possible to consider progression in understanding the chemical bond. Figure 12.2 uses this form of schematic to consider the case of an 'ideal' candidate for the A level chemistry examination. This individual has a wide selection of conceptual tools from CURRICULUM SCIENCE related to bonding to use in answering examination questions relating to chemical bonding. Figure 12.2

also suggests that the 'ideal' candidate may have developed two complexes of conceptions from these conceptual tools so that explanations do not need to be constructed ab initio: one based around the principles of quantum theory (Q), and the other Coulombic forces (C). Moreover these two complexes are integrated to some extent.

In this research it was found that on commencing an A level course students were more likely to reflect the level of cognitive resources shown in figure 12.3. For one thing, at this stage the learner has many fewer conceptual tools relevant to the topic area. (And even those concepts that are available will not match the 'versions' of the concept in figure 12.2, so that - for example - the concept *ionic bond* may mean something quite different in the two cases.)

At least as significant is the *absence* of the complexes 'Q' and 'C'. At this stage the student is unlikely to have any notions of orbitals or other quantum concepts. The complex labelled '*E*' represents electrostatic ideas. Typically the learner will use the ideas of attractions and repulsions between charges in some of his or her explanations for chemical phenomena. However, this complex is not strictly 'Coulombic' (although it may be *developed* to become similar to 'C'), as it is likely to incorporate alternative notions to the Coulombic electrostatics of CURRICULUM SCIENCE (such as CONSERVATION OF CHARGE).

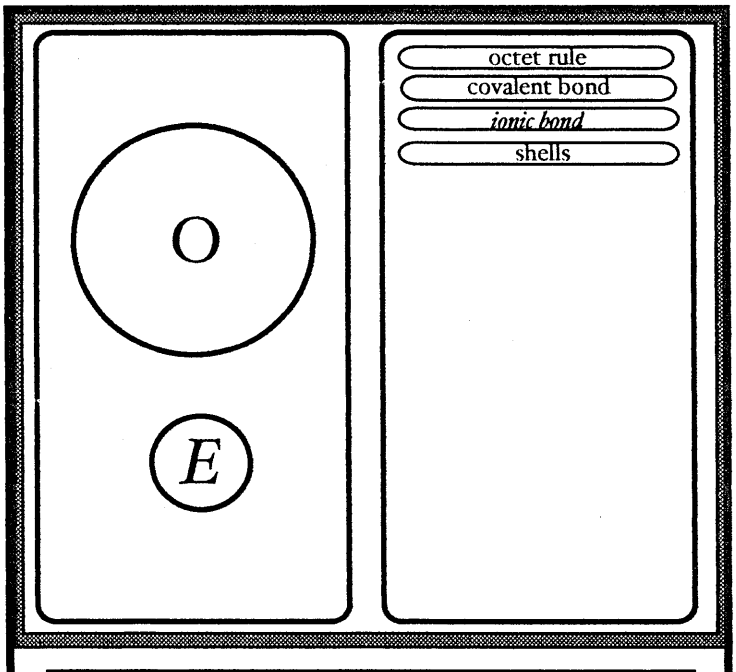


fig.12.3 - cognitive resources of colearners at start of course

The A level inductee (fig.12.3) typically uses '*E*' much more sparingly than the ideal examination candidate uses 'C' (fig.12.2). Instead most explanations about bonding are constructed from the alternative OCTET RULE FRAMEWORK (O). Figure 2.3 may stand as a general model for the colearners in this study when they began their A level courses, although the details would vary from one individual to another.

The role of the A level chemistry teacher could be seen as guiding the learner by providing the scaffold of experience that facilitates progression from the type of structure represented in figure 12.3 to that in figure 12.2. Tajinder provides an example of a real student, who obtained the top grade in the A level chemistry examination. Yet the research shows that he did not develop his cognitive structure to match figure 12.2. In his case figure 12.4 would be a better representation of this aspect of his cognitive structure by the end of his course,

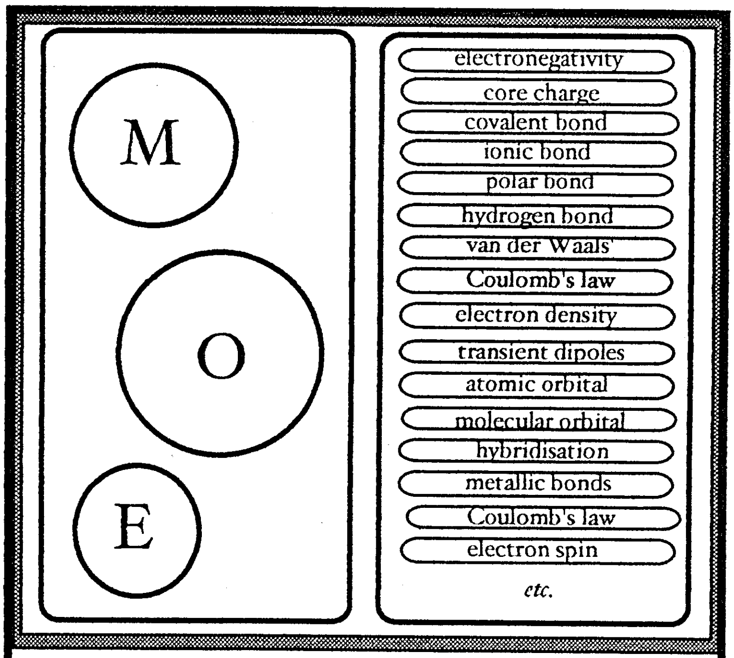


fig.12.4 - cognitive resources of Tajinder before his exams.

Tajinder demonstrated that he had acquired a full range of conceptual tools relating to chemical bonding (§8.4.1); however he did not develop the type of unified 'Q/C' framework suggested in figure 12.2. Rather he operated with three largely discrete explanatory principles (§8.4.5). 'E' reflects an electrostatic framework, that may be understood to be a developed version of the corresponding component (*E*) in figure 12.3. Similarly, the 'O' in figure 12.4 may be seen as being largely unaltered from that shown in figure 12.3. Although *octet thinking* dominated Tajinder's explanations much less at the end of his course when he had alternative explanatory principles, it remained a major component of his thinking (§8.4.4).

'M' represents a framework of ideas constructed around Tajinder's MINIMUM ENERGY EXPLANATORY PRINCIPLE and using the conceptual tools of 'orbitals' and 'energy levels'. This developed some way towards 'Q' in figure 12.2, but did not become integrated with his electrostatic framework.

However, the most significant difference between figures 12.2 and 12.4 is the presence of 'O' in Tajinder's cognitive structure. If similar figures were drawn for the other colearners at the end of their courses they would also include frameworks of this type, and in most cases they would be major components of the student's cognitive structure. It would seem that - at least in the cases studied - *acquiring additional conceptual tools is easier than dismantling existing explanatory frameworks.* Indeed the analysis of chemical knowledge presented in chapter 1 suggests that - in general - it would not be appropriate to completely discard chemical tools (c.f. §1.7.2). Usually new conceptual tools supplement rather than substitute existing ones.

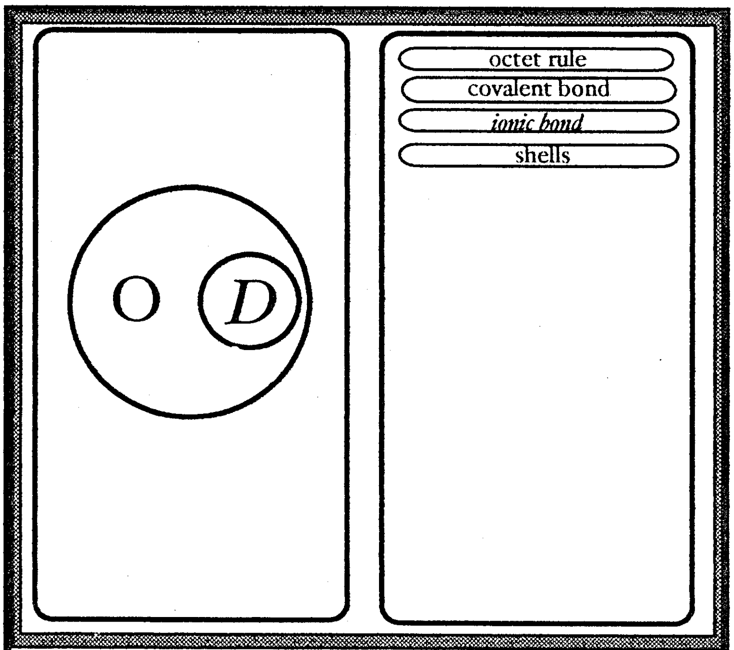


fig.12.5 - cognitive resources of Annie at the start of her course

As Tajinder was a successful student, it might be appropriate to compare his case with that of Annie (who obtained a lower grade in the A level examination: D c.f. A). She also acquired some new conceptual tools related to bonding during her course (§7.1). Like Tajinder, she retained *octet thinking* through her course (§7.3.1). Although - like Tajinder - she acquired an electrostatic explanatory principle, this was less developed by the end of her course (§7.3.2). One factor here is that at the start of her course Annie did not seem to use conventional electrostatic notions. Although she talked of charges, and used them in her explanations, for Annie these were her DEVIATION CHARGES (D, §7.2.2), which were already a key part of her STABLE SHELLS EXPLANATORY PRINCIPLE (O).

So for Annie, not only did she commence A level - like most of her peers - without the components needed to construct a framework such as 'Q', but she also lacked the basis to form a framework such as 'C'. Whereas most of the colearners at least had a relevant electrostatic explanatory principle on which to build (figure 12.3), Annie did not (figure 12.5).

Annie may be considered to have commenced A level studies with a double handicap: her STABLE SHELLS EXPLANATORY FRAMEWORK acted as a SUBSTANTIAL LEARNING IMPEDIMENT (shared with the other colearners) so that she did not see the need for the explanations of CURRICULUM SCIENCE; and her ignorance of conventional electrostatics meant that there was a NULL LEARNING IMPEDIMENT (that the other colearners did not share) so that she had little relevant structure to relate to electrostatic explanations she met. (In addition the notion of DEVIATION CHARGES acted as an additional SUBSTANTIAL LEARNING IMPEDIMENT to acquiring the conventional notions of charge).

§12.4.2: Barriers or bridges: stepping stones revisited.

In chapter 2 it was pointed out that whilst some researchers seem to view learners' alternative ideas in science as necessarily *'barriers'* to the learning of CURRICULUM SCIENCE, the constructivist view focuses on the importance of current cognitive structure as resources for learning, and sees alternative conceptions as potential *bridges* to desired learning (§2.3.9). Although the present research has been undertaken within a constructivist frame, it has taken a pragmatic stance that it is necessary to model progression in understanding chemical bonding, and to diagnose common learning impediments to that progression *whether* the alternative ideas elicited are to be considered as obstacles to be demolished *or* to be seen as the foundations for constructing new knowledge.

Although this study investigated some of the individual colearners' thinking over a period of two academic years, this was *not long enough* to give a clear idea of whether some of the alternative ideas elicited were best seen as *stepping stones* to curriculum science.

It would certainly be possible to analyse elicited alternative conceptions to compare them with their CURRICULUM SCIENCE 'targets'. For example, Annie's deviation charges may be compared to the electrostatic charges of CURRICULUM SCIENCE

conception:	deviation charge	electrostatic charge
status:	alternative	curriculum science
label:	charge	charge
types:	positive & negative	positive & negative
action:	opposite - attract similar - repel	opposite - attract similar - repel
charge on atoms changed by	addition or removal of electrons	addition or removal of electrons
atom made more positive by:	given extra electron	removal of electron
defined by:	deviation from desired electronic configuration	basic ontological category
charge found on:	most atoms	ions
uncharged:	stable ions, noble gas atoms, atoms with extra octets atoms with missing octets	atoms (not ions)

table 12.1

Annie's DEVIATION CHARGE conception compared with CURRICULUM SCIENCE

Table 12.1 shows that there were a number of ways in which Annie's use of 'charge' matched the accepted meaning. Yet it seems clear from the case study that Annie's DEVIATION CHARGE notion was *not* helpful as an *intermediate conception* on a *conceptual trajectory* (§2.3.10) to understanding electrostatic charge (see §7.2.2). Indeed, it was the similarities of Annie's conception with the curriculum version which allowed her to make sense (i.e. form a coherent *alternative* interpretation) of explanations from the CURRICULUM SCIENCE perspective given by teachers and texts, and thus helped *reinforce* her alternative meanings (c.f.2.3.6).

Conversely, Tajinder's MINIMUM ENERGY EXPLANATORY PRINCIPLE, certainly *could* be considered as an *intermediate conception* on a potential *conceptual trajectory* (§2.3.10) to understanding chemical processes. Like Annie's DEVIATION CHARGES, this explanatory principle has similarities and differences with orthodox science.

Tajinder's notion was not identical to the CURRICULUM SCIENCE version because it was not integrated with his ideas of force and equilibrium. Yet it was basically a sound principle. It might have acted as an EPISTEMOLOGICAL LEARNING IMPEDIMENT had Tajinder's use of this principle *excluded* his thinking in other terms. Yet Tajinder's acceptance of plural explanatory schemes (§8.4.5) meant that he could explain a phenomenon in terms of minimising energy, then re-examine the phenomenon from a different perspective (such as the effect of forces).

Although Annie eventually learnt about *electrostatic* charges, her DEVIATION CHARGES tended to come to mind first, and the two meanings were mutually exclusive (§7.2.2).

In Tajinder's case, knowledge of his MINIMUM ENERGY EXPLANATORY PRINCIPLE could inform a teacher hoping to provide a scaffold (§2.2.2) to facilitate the eventual *integration* of this principle with his COULOMBIC FORCES EXPLANATORY PRINCIPLE. The teacher aware of this cognitive resource could use it as the basis of constructing knowledge. In Annie's case, the DEVIATION CHARGES conception was not a useful resource for learning about chemistry.

In both cases the diagnosis of the learner's ideas was important: in one case to identify the conceptual foundations in place, in the other case to identify a notion that would need to be challenged (c.f. §2.8.3).

§12.4.3: The octet rule framework as a stepping stone?

The FULL SHELLS EXPLANATORY PRINCIPLE is *not* valid as a scientific explanation of *why* bonding occurs. However the present research suggests that it provides a rationale that is readily adopted by learners. This principle undoubtedly acts as a SUBSTANTIVE LEARNING IMPEDIMENT which interferes with learning of the models of CURRICULUM SCIENCE (as is documented in detail in chapter 11).

One possibility is that the FULL SHELLS EXPLANATORY PRINCIPLE acts as a *totally unnecessary* EPISTEMOLOGICAL LEARNING IMPEDIMENT that could be avoided by appropriate changes to pedagogic practice. This possibility is considered below, where advice is given on how teachers can avoid their students developing *octet thinking* (§12.5).

However, application of the OCTET RULE FRAMEWORK *does* demonstrate that students have an understanding of the basic chemical idea of substance, and also hold a fairly detailed version of atomic theory (understanding the relationship between atoms and elements; appreciating sub-atomic structure, and the notion of electronic configuration; distinguishing atoms, molecule and ions). Chapter 3 (particularly §3.1.1 and §3.1.2) reported how many learners have great difficulty with these abstract concepts. So while use of the OCTET RULE FRAMEWORK may be an impediment to conceptual development at one level, it also demonstrates that a range of difficult scientific ideas have been learnt.

It is certainly true that the progression from ignorance of the chemical ontology of elements, compounds and mixture, to an understanding of chemical substances and processes in the terms represented in figure 12.2 represents a vast degree of conceptual development. This present research project has only investigated a small part of this development, yet the case studies presented in chapters 7 and 8, as well as the supporting evidence from other learners presented in chapters 9 through 11, demonstrate the long-term nature of such conceptual growth.

It may be that the gap between complete ignorance of atomic ideas and the type of understanding expected of the 'ideal' A level candidate represents a chasm in cognitive structure that few learners could effectively cross by age 18 (when the A level examination is most commonly taken). Perhaps this 'chasm' acts as a DEFICIENCY LEARNING IMPEDIMENT so vast that progression is only possible for most learners when appropriate *stepping stones* are available (§2.3.10). The orthodox scientific rationale may be so alien to learners' intuitions that alternative *intermediate conceptions* are required that learners can more easily relate to.

If this is the case, the FULL SHELLS EXPLANATORY PRINCIPLE may be taking on this role. Perhaps some aspects of the OCTET RULE FRAMEWORK have particular appeal to learners (such as the *sea of electrons* metaphor, §11.6.4). Perhaps there is a gestalt for *dichotomising* experience (§11.6, c.f. Kelly's bipolar construct systems, §2.2.4).

Whatever 'stepping stones' may be needed to allow learners to develop the highly abstract concepts of chemistry would need to bridge with their existing experience of the world. One candidate for such a bridge would be the anthropomorphic language of the OCTET RULE FRAMEWORK which allows a learner to think about atomic systems in analogy with the more familiar social context.

§12.4.4: Anthropomorphic language.

The phenomenon of students using anthropomorphic language to describe the 'behaviour' of particles such as molecules and electrons is reported in the literature (§3.1.4). In the present study this type of language was found to be common amongst the utterances of A level students (§11.3). Indeed I have proposed that anthropomorphic language is an integral part of the OCTET RULE FRAMEWORK. The implication of my research is that such language stands *in place of* appropriate scientific explanations.

However, I would argue that anthropomorphic language *need not necessarily* be a undesirable thing in learning science. If one accepts that the human conceptual system largely develops through analogy (§2.4.4), then it could be argued that anthropomorphism may be seen as a means of making unfamiliar systems comprehendible *by comparison* with the familiar behaviour of people. Indeed, anthropomorphism may be seen to have been used for pedagogic purposes by scientists. It was pointed out in chapter 3 (§3.1.5) that anthropomorphic and animistic language may be used in a quite explicit way in science, and that it has been seen as valuable in increasing the appeal of school science.

Explanation and understanding. In science explanation tends to be most valued if in terms of causality: effects are explained by their causes; good theories explain a large range of phenomena in terms of a small number of fundamental causes. Often a sufficient 'cause' at one level of explanation is itself a phenomenon that needs to be explained at a more fundamental level. For the active scientist explanation is likely to be in terms of mechanism and logical reasoning.

Few scientists - cosmologists excepted - are searching for the ultimate cause, and this is often illustrated with the idea that the biologist uses the ideas of the chemist who in turn uses the ideas of physics. Despite being an extreme simplification there is indubitably some truth is this idea: when Crick, Franklin, Wilkins and Watson 'solved' the D.N.A. structure 'problem', they became widely celebrated: Crick and Watson especially. They were no less scientists for having to take as given a considerable amount of knowledge about keto-enol tautomerism, X-ray diffraction techniques, hydrogen bonding etc., without deriving such ideas from 'first principles'. Perhaps what scientists, but not necessarily our students, do is think at several levels at once (e.g. D.N.A. as a functioning unit carrying a code in heredity, D.N.A. as a macro-molecule composed of sub-units of bases and sugars, D.N.A. as comprised of atoms bonded together, D.N.A. as a structure which can be investigated by physical techniques, D.N.A. as a substance found in chromosomes, etc.), and use *description* at one level to *explain* a phenomenon at another.

In school and college science we are concerned with developing understanding. Ultimately we want our students to be able explain phenomena in a logical manner - but understanding is not an all or nothing process. The learner constructs meaning, and construction tends to be a piecemeal process that requires good foundations, and may require the use of temporary scaffolding and supports - to be removed later when the structure is complete (c.f. §2.2.2). Understanding may often start at a 'descriptive' level, and only when the description is familiar can causes be considered (or different *levels of explanation* be developed - in the terms of the paragraph above). Teachers (and scientists) communicate meaning through the use of analogy and metaphor, to compare the novel phenomenon with ideas familiar to the audience (§3.1.5).

It would follow from such considerations that *metaphorical* anthropomorphism is to be encouraged. We should approve when students use such language as part of their early attempts to make sense of aspects of science. Nuclei, electrons and bonds are small and abstract compared to the objects of direct experience of young people. Appropriate analogies can act as an introduction to this microworld.

Two classes of anthropomorphism. Metaphorical anthropomorphism, or perhaps 'weak' anthropomorphism, is seen as a virtue. If Jagdish is well aware that atoms do not *want*, *realise*, *feel* or experience happiness, but uses such terms to communicate her ideas about the sodium atom in analogy with a social being, then this is a healthy stage between ignorance of the atomic world and being able to express her ideas in the more physical (and alas perhaps less poetic) language of energy and forces, and solutions to the Schrödinger equation (§11.3.3). But if Jagdish thinks a sodium atom literally experiences its world through feelings and emotions much like hers, then it is but a short step to explaining chemistry through the feelings of atomic species. (So, for example, sodium atoms react with chlorine molecules because they *want* to.) When Schrödinger asked if electrons think (§3.1.5) it was a rhetorical question, but the findings from the present study suggest that perhaps such questions are not rhetorical for some students. This 'strong' version of anthropomorphism is teleological, in that it allows phenomena to be explained in terms of the (non-existent) desires of atomic species to achieve the end-state.

I am suggesting that strong anthropomorphism is being used when bonding is seen to enable atoms to 'achieve' or 'attain' a full outer shell. Some students interpret the 'full outer shell' as a *sufficient* explanation for chemical reactions - atoms react to form molecules or ions because they *want*, or *need*, to achieve a full outer shell. If the student considers that such teleological anthropomorphism is a *sufficient* cause of the chemical change, then he or she has no reason to seek other levels of explanation (say in terms of potential energy and electrical fields). For this reason I suggest that such 'strong' anthropomorphic thinking could actually be an impediment to further learning.

However, it could also be argued that perhaps strong (teleological) anthropomorphic language is the first stage in developing understanding, allowing the learner to obtain a descriptive level of understanding of atomic-level phenomena through mental role-play and empathy. Maybe as the abstract atomic world becomes familiar through such 'social' modelling the learner is able to move past the descriptive level (but perhaps retaining anthropomorphic language to be used metaphorically, or simply as habit). So it is possible that even strong (teleological) anthropomorphism may be a *stepping stone* on an appropriate *conceptual trajectory* (§2.3.10).

Such uncertainty suggests that more work should be undertaken to investigate children and young people's use of anthropomorphic language (see §12.6).

12.4.5: An alternative conceptual trajectory?

To summarise my argument: the OCTET RULE FRAMEWORK represents a complex of related ideas that were demonstrated to differing extents by chemistry students in the study, and which were based around the FULL SHELLS EXPLANATORY PRINCIPLE This principle seems to be a common alternative conception, in that it was used to some extent by all the colearners interviewed. In that

(a) the FULL SHELLS EXPLANATORY PRINCIPLE offers an alternative rationale to the explanations of CURRICULUM SCIENCE, and

(b) that the OCTET RULE FRAMEWORK is not consistent with the 'target' level of understand of chemical bonding desired at A level,

these aspects of student thinking may be considered to be SUBSTANTIVE LEARNING IMPEDIMENTS.

However, given that the CURRICULUM SCIENCE models of bonding are very abstract and based on a range of prerequisite topics that are known to present difficulties, it may be that the OCTET RULE FRAMEWORK acts as a *stepping stone* to *bridge* between a student's ignorance of atomic and sub-atomic phenomena and the desired understanding.

Yet even if the OCTET RULE FRAMEWORK is seen in this light, the present research suggests that progression from *octet thinking* to applying CURRICULUM SCIENCE models is unlikely to be complete by the end of an A level course. Tajinder was a well motivated and able student who achieved the highest grade in his A level examination. He had supplemented his A level studies with his participation in the research. The long sequence of in-depth interviews where his Z.P.D. (§2.2.2) was probed through the scaffolding of relentless questioning might be expected to closely match the conditions where learning was most likely to occur (§2.2.3). Yet even Tajinder's conceptual development fell short of the target understanding.

One possible conclusion is that, as far as understanding chemical bonding is concerned, the requirements of A level chemistry syllabuses are unrealistic for the vast majority of learners. However, an alternative approach would be to ask if there is another *conceptual trajectory* which might more effectively allow learners to progress to the target understanding. Figure 12.6 illustrates this idea.

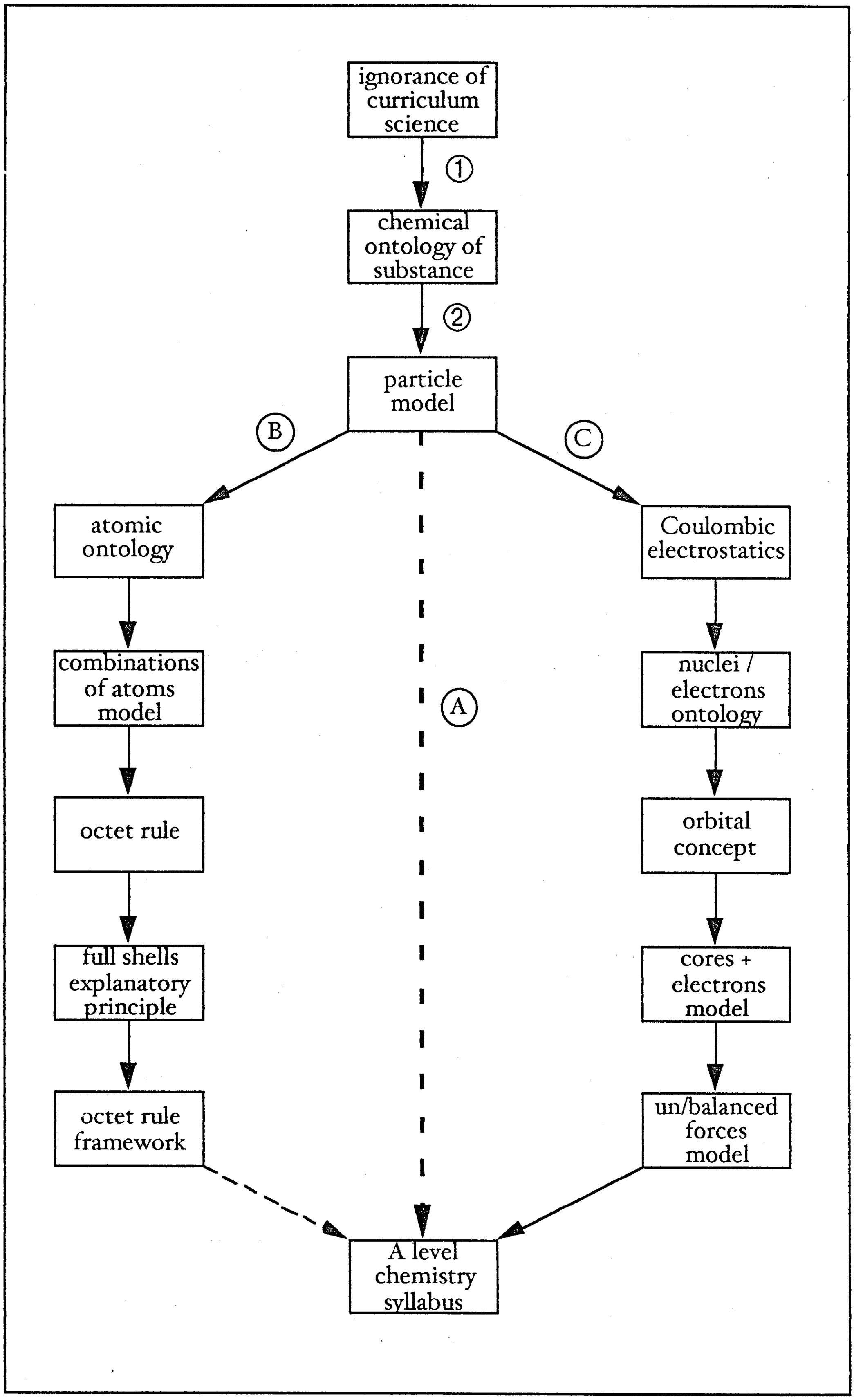


figure 12.6: two conceptual trajectories towards understanding chemical bonding

In this figure it is assumed that a learner needs to progress from an ignorance of relevant CURRICULUM SCIENCE ideas, to an understanding of chemical bonding which matches the A level chemistry syllabus.

The learner would need to (1) adopt the chemistry ontology of substance (elements, compounds mixtures) which it is known is counter-intuitive to most young children (§3.1.1). The learner would also need to (2) accept the basic premise of the particle model of matter. This would include appreciating the properties of bulk matter are explained by particle theory, but that the particles themselves do not possess macroscopic attributes - another difficult idea for learners (§3.1.2). Even with these prerequisite foundations in place, a great deal of conceptual development (A) is required to reach an understanding of chemical bonding that satisfied A level syllabus requirements. For meaningful learning to take place, this development would need to proceed by manageable steps, allowing the learner to *assimilate* or *accommodate* (§2.10.1) each novel concept before the subsequent step is taken.

At present (path B), a learner's first introduction to particle theory could involve the use of terms such as *atoms* and *molecules* without any clear distinctions being drawn (see appendix 7, §A7.4.2, §A7.5). However, in chemistry instruction the emphasis is likely to be on *atoms* as the basic constituents and building blocks of matter. It follows from this that molecules and lattices will be conceptualised as *combinations of atoms*, and ions will be seen as *altered atoms*. In explanations of these combinations and alterations of atoms, the learner will meet the octet rule. Although the octet rule *may be* presented in terms that are perfectly valid from a CURRICULUM SCIENCE perspective (but *may not be*, see appendix 33, §A33.11), the evidence from this study suggests that overwhelmingly learners will adopt the FULL SHELLS EXPLANATORY PRINCIPLE to explain chemical reactions and chemical bonding. It was not possible in this research - when the learners already held this principle - to know the extent to which the explanatory principle may be explicitly taught or implied by teachers and texts, or is personally constructed from the octet rule by individual learners, or may be formed as part of the social consensus developed between pupils trying to make sense of their school lessons. However, it was found that the learner will develop a range of ideas related to this explanatory principle, which collectively I have modelled as the OCTET RULE FRAMEWORK.

From this position the OCTET RULE FRAMEWORK *may* act as a *stepping stone* to the required understanding, although the conceptual change needed for this step may require more time than is available in an A level course. My own research would suggest that the OCTET RULE FRAMEWORK is too different from the CURRICULUM

SCIENCE perspective to allow a ready transformation, and it is quite likely that instead it may be retained in cognitive structure as one of a number of multiple frameworks for the topic.

Given that even if the OCTET RULE FRAMEWORK can be seen as a ***stepping stone***, it does not seem to be a particularly effective one, it seems sensible to consider an alternative trajectory. One possibility is included on fig.12.6. In this path (C), there is no discussion of atoms until other material has been learnt. The learner is taught about Coulombic electrostatics. At the present time this may be ***assumed*** prerequisite knowledge, and ***implicit*** in explanations given to students, but this research demonstrates that learners may not share CURRICULUM SCIENCE electrostatics, and - in any case - often do not see its relevance to chemical explanations).

Once learners are familiar with Coulombic electrostatics they are presented with an ontology of the basic building blocks of chemistry being charged particles: nuclei and electrons. These entities would be understood in terms of their Coulombic interactions.

The next step would be to introduce the orbital concept as restricting the possible locations of electrons *in any system* so that the configurations that nuclei and electrons take up when they interact are subject to additional constraints superimposed on the electrostatic considerations.

Only then would the atom be formally introduced. The learner would first be introduced to systems of nuclei, and shells of electrons making up ‘atomic cores’. Then further systems of cores and electrons would be considered. An atom is a system of a single atomic core plus sufficient electrons for the charge on the electrons to balance that of the core. Ions and (polynuclear) molecules are other possible systems.

Chemical change can then be explained as changes in the configurations of cores plus electrons brought about by unbalanced forces. Bonds may be understood as stable configurations of cores plus electrons that require a significant energy input to disturb them from equilibrium. The learner would then have appropriate knowledge to apply to the content of the A level syllabus.

It may prove that such a trajectory is not feasible within the time available for most learners, as the concepts involved are too abstract. Yet this present research suggests that although learners readily adopt the OCTET RULE FRAMEWORK, they then have difficulty progressing beyond *octet thinking* even when it cannot explain the phenomena they are asked to consider. An alternative trajectory more closely tied to the target understanding (such as path C in fig.12.6) might be more effective as long as the teaching sequence explicitly supplies the required knowledge in a logical order, and in manageable steps.

§12.5: Advice to teachers, teacher educators, textbook authors and curriculum planners.

As a result of the research reported here it is possible to offer advice about the teaching of chemistry. My main recommendations would be:

- Introduce electrostatics early.
- Avoid over-emphasis of the octet rule, octets, full shells etc.
- Present an ontology based on systems of nuclei and electrons.

1. Introduce electrostatics early. The development of octet thinking is tied to a perception of the octet rule as the cause of chemical bond formation. It seems likely that this is at least partly because of a NULL LEARNING IMPEDIMENT:

(a) learners do not have an awareness of basic electrostatics (a DEFICIENCY LEARNING IMPEDIMENT), or

(b) they do not see the relevance of electrostatics to *chemistry* (a FRAGMENTATION LEARNING IMPEDIMENT).

I would recommend that from the time that atoms and molecules are first taught, the electrostatic nature of the interactions between sub-atomic particles is made clear, and emphasised.

I would conjecture that if learners had reason to perceive electrostatic forces as the 'cause' of chemical interactions, then they would not feel a need to adopt the octet rule as an inappropriate explanatory principle. It would be useful for further research to be undertaken to explore the effectiveness of this recommendation.

2. Avoid over-emphasis of the octet rule, octets, full shells etc. In the present research no attempt was made to observe teaching, to find out if learners' acquisition of an OCTET RULE EXPLANATORY PRINCIPLE was truly a *mis*conception of what their teachers had said, or perhaps in some cases the result of the teacher him/herself using *octet thinking*. However, some introductory text books certainly lend themselves to interpretations which would support *octet thinking* (see appendix 33, §A33.12). Firstly, they may treat the terms *octet* and *full outer shell* as synonyms, and thus give students incorrect information about electronic configurations for heavier elements (which is not a problem at the intended level, i.e. up to G.C.S.E., but requires 'unlearning' at A level).

The 'octet rule' is really concerned with the stability of noble gas electronic configurations. The term *octet* means a set of eight electrons, and therefore is technically inappropriate for period 1 (hydrogen and helium). For periods 1 and 2 the noble gas electronic configuration *is* equivalent to having electrons shells that are all either full or empty, thus the term 'full outer shell'. However for period 3 and beyond noble gas structures do *not* involve full outer shells. Argon is ten electrons short of a full outer shell, and Xenon is not only 24 electrons short of a full outermost shell, it is also 14 electrons short of a full outermost-but-one shell. Yet elementary text book authors ignore these complications, and tell their young readers that atoms are stable *if* they have full shells (§11.2.6 and appendix 33, §A33.12).

It might be argued that it is acceptable to introduce the idea of full outer shells as a general notion, provided that when period 3 elements are considered the idea is developed. Yet the texts reviewed included specific references to the third shell being full when it held eight electrons, and chlorine and neon atoms were described as having full shells. One book that did acknowledge that the third shell was *not* full when it held an octet justified treating it *as* a full shell on the basis that eight electrons in the third shell *behaved like* a full shell (appendix 33, §A33.12). (This is circular logic: the stability that is found to be associated with an outer-shell s^2p^6 configuration is inappropriately regarded as being due to a full shell. Then when it is acknowledged that the stable configuration is not necessarily a full shell, it can be considered to behave *like* a full shell because it exhibits the stability - inappropriately - associated with full shells, but actually inherent in the configuration.)

More significantly some introductory texts I have consulted seem to use the octet rule *as an explanatory principle*, rather than as a heuristic. Although the idea may be initially presented as an observed *correlation* between certain electronic structures and chemical stability, subsequent text may imply that stability is therefore *explained* by noble gas configurations (see appendix 33, §A33.11).

Having an *octet* does not intuitively suggest stability, but the catchy phrase "full outer shell" may well do - even though it is technically suspect. Once the notion of full shells being stable is established, it may then be used to explain the 'purpose' of bonds. Further, as bonds are formed during chemical reactions the 'explanatory principle' may be extended to explain the reactions themselves.

What is ignored when such statements are made is that in chemical reactions bonds are broken as well as made, so that although the *octet rule* could 'explain' why atomised materials would 'react', it has little relevance to the chemistry that is met in school, industry or everyday life.

3. Present an ontology based on systems of nuclei and electrons. The present study found that the A level chemistry learners investigated appeared to operate with an ontology of the sub-microscopic world based on the atom as the unit of matter (§11.1).

In practice two objections may be made to this, one in terms of quantum mechanical (orbital) thinking, and one in more general terms. In quantum mechanical terms it may be argued that the atom as conceptualised in elementary textbooks is an idealisation which does not exist in the real world. Our concept of an atom is of a discrete structure which comprises of a nucleus and one or more electrons in atomic orbitals. In the sense of this *theoretical construct* the atom certainly exists: evidence may be found in books, examination papers, pupils' exercise books and so forth. Our concept of the atom also has the feature that atomic orbitals have infinite extent, and that when the atomic orbitals of two different atoms overlap they interact to form molecular orbitals. It follows logically that it is not possible for a discrete atom to exist, unless it was the only atom in the universe. In our universe the atoms must perturb each other to some extent, and therefore they are no longer - strictly speaking - distinct atoms, but rather part of some immense 'molecular' structure.

However, although the universe could not contain entities that totally match the theoretical concept, it is often sensible to consider that discrete atoms do exist. This is appropriate when one system of a nucleus and electrons is so little perturbed by others that we can ignore the interactions. I will call this *the atomic approximation*, justified as a 'first approximation' in many systems, providing we accept that we are simplifying, which always involves the loss of some detail.

My second point is that the chemical community has a *historically rooted ontological commitment* to the atom as the building block of matter (c.f. §1.6). The original notion of atom was something *atomos*, indivisible. The last 100 years has shown that not only is the atom not a candidate, but that it is the very divisibility of atoms that gives us chemistry at all. Yet the atom is still presented as the basic unit in which to discuss chemistry. I believe that this ontological commitment may be seen in the way in which chemical bonding is usually described 'historically' in terms of bond formation between ***atoms*** (and indeed taking up Benfey's point about molecular *life-histories*, see §3.1.5, this might be related to the high incidence of anthropomorphism discussed above, §12.4.4). I would argue that such an approach is mythical: in our physical environment, during the present cosmological epoch, chemistry seldom occurs between atoms. Indeed, most atoms are relatively unstable, and those that tend to be stable (i.e. the noble gas atoms) do not have much chemistry - they do not tend to form bonds readily.

The implication that common materials are formed from atomised matter. Chemical reactions of importance in the real world consist of processes involving relatively stable materials. This is even true for reactions such as binary syntheses that have little relevance in industry, the environment or biology, but which are considered useful as illustrations in the school or college laboratory.

	MOLECULAR FRAMEWORK	ELECTROSTATIC FRAMEWORK
status	ALTERNATIVE FRAMEWORK2	CURRICULAR SCIENCE
role of molecules	ion-pairs are implied to act as molecules of an ionic substance	ionic structures do not contain molecules - there are no discrete ion-pairs in the lattice
focus	the electron transfer event through which ions may be formed	the force between adjacent oppositely charged ions in the lattice
valency conjecture	atomic electronic configuration determines the number of ionic bonds formed (e.g.: a sodium atom can only donate one electron, so it can only form an ionic bond to one chlorine atom)	the number of bonds formed depends on the coordination number, not the valency or ionic charge (e.g.: the coordination is 6:6 in NaCl)
history conjecture	bonds are only formed between atoms that donate / accept electrons (e.g.: in sodium chloride a chloride ion is bonded to the specific sodium ion that donated an electron to that particular anion, and *vice versa*)	electrostatic forces depend on charge magnitudes and separations, not prior configurations of the system (e.g.: in sodium chloride a chloride ion is bonded to six neighbouring sodium ions)
'just forces' conjecture	ions interact with the counter ions around them, but for those not ionically bonded these interactions are just forces (e.g.: in sodium chloride, a chloride ion is bonded to one sodium ion, and attracted to a further five sodium ions, but just by forces - not bonds)	a chemical bond is just the result of electrostatic forces - ionic bonds are nothing more than this (e.g. the forces between a chloride ion and each of the neighbouring sodium ions are equal)

Table 12.2.
A comparison of the molecular framework and curriculum science explanations of ionic bonding

If sodium chloride is required it will be found in natural deposits. If we require a laboratory preparation we might chose a neutralisation process. If we wished to demonstrate binary synthesis of sodium chloride our reagents would be *metallic* sodium and *molecular* chlorine as these are the elemental forms. Yet again examination of some elementary textbooks revealed that the reaction between sodium and chlorine was described and illustrated *as if* between individual atoms of sodium and chlorine, which undergo electron transfer to form ion pairs (appendix 32, §A32.5). Such a presentation clearly reflects the 'molecular' framework for understanding ionic bonding (see appendix 2, §A2.0) which includes a number of common aspects of *octet thinking* described in chapter 11.

Table 12.2, above, presents a comparison between the molecular and conventional CURRICULUM SCIENCE interpretations of ionic bonding, as discussed in appendix 2. It will be noted that the components of the ALTERNATIVE CONCEPTUAL FRAMEWORK2 make up a subset of the OCTET RULE FRAMEWORK discussed above.

Similar presentations were found in text book descriptions of the reactions between hydrogen and chlorine, hydrogen and fluorine, magnesium and chlorine, hydrogen and carbon, and hydrogen and oxygen (see appendix 32, §A32.5). In the latter cases isolated atoms were drawn even when several 'molecules-worth' of reactant atoms were required for the reaction! So these strangely irrelevant diagrams cannot be explained as representing real chemical processes, nor as due to some kind of graphical economy. Three possibilities are:

1: The diagrams are not meant to represent chemical processes of our world, but the primeval formation of molecular matter in some previous cosmological epoch.
2: Diagrams of this form are used because this is the way the authors were taught, and it has not occurred to them that they are misleading.
3: The authors are aware of the inaccuracy of the diagrams, but chose to use them because they are consistent with the (invalid) explanation of chemical processes in terms of achieving full shells.

The first option would seem to be rather obscure, unless there is some presupposition that the 'natural state' of matter (i.e. that which does not need to be explained, see the discussion of the *explanatory gestalt of essence* in chapter 2, §2.4.4) consists of atoms; and materials in our world do need to be derived from such a starting point. That is, that the authors are following an atomic ontology. This is perhaps not completely fanciful as the notion of elemental atoms predates the science of Dalton, Rutherford and Bohr by many centuries.

If the second possibility were to be correct it would certainly support the notion of the FULL SHELLS EXPLANATORY PRINCIPLE as an (epistemological) learning impediment, and suggests its efficacy is so great as to effect *generations* of learners.

The third possibility would seem to suggest a somewhat cynical attitude on the part of authors who are aware they are presenting misleading information, but chose to develop the deceit rather than find a more intellectually valid approach.

The present study suggests that chemistry learners may adopt similar approaches, producing diagrams (see chapter 11 and appendix 35) similar to those textbook figures I criticise here.

Yet where the chemical 'history' of substances are known, they have not originated from isolated atoms of the elements. Where the history of substances is not known, CURRICULUM SCIENCE informs us that it is irrelevant: a substance with a given chemical formulae has properties that do not depend upon how it was prepared (for example copper oxide, CuO, should be the same if prepared by heating copper in oxygen, or by thermally decomposing copper carbonate). The assumption that one starts with isolated atoms of the elements is then incorrect, and should be an irrelevance. Yet this simple error provides the justification for ***raising the octet rule to the status of an explanatory principle***. The octet rule does indeed provide an effective heuristic for predicting stable chemical structures, but can provide no rationale for the vast majority of chemical processes of interest, where both reactants and products 'obey' the rule.

My own recommendation would be to give the highest status to different species in the sub-microscopic ontological zoo: *electrons* and *nuclei*. Although nuclei are not immutable, their reactions are the domain of physics. In chemical processes nuclei and electrons retain their integrity.

I would recommend that when it is judged learners are ready to tackle the theoretical models of sub-microscopic particles they are introduced to nuclei and electrons as the basic 'building blocks' of chemical systems. Atoms, ions and molecules may then be given equal status as a higher level of structure. At an advanced level the notion of atomic cores (nuclei plus 'inner' shells of electrons) may be emphasised, with the core taken as an important sub-system which with valency electrons makes up atoms, molecules, and ions. These structures should be explained in terms of the electrostatic attractions and repulsions acting between the nuclei and electrons in the system. Chemical processes should be explained as rearrangements of the system.

I would also recommend that these re-arrangements need to be taught in terms of electrostatic forces, (electrostatic) potential energy, and quantum shells (with a maximum number of electrons allowed). I would argue that if these ideas cannot be presented in some intellectually valid way that learners can understand, then these learners are not ready to learn about chemistry at the sub-microscopic level.

The alternatives to this are are to provide an invalid basis, or no rationale at all, for chemical systems and chemical change. In the latter case, the present research suggests, learners will develop their own reasons for chemical reactions. In either case the learners are likely to develop ideas that do not provide a suitable basis for advanced work, and interfere with the later acquisition of the accepted CURRICULUM SCIENCE models.

§12.6: Suggestions for further research.

The limited scope of the present study means that there are many avenues of work which could build on this research. Some of these are:

1. It would be possible to *survey* the occurrence of some of the learners' alternative ideas presented in this study: the CONSERVATION OF FORCE conception, and aspects of the OCTET RULE FRAMEWORK. (This could build on the provisional work reported in appendices 2 and 3.)

2. Where learners study *both* chemistry and physics it would possible to investigate whether the same alternative ideas about electrostatics are elicited in both subjects - or whether this knowledge is compartmentalised according to perceived subject boundaries (c.f. Paminder's comment (§A3.2) that "I can't think about physics in chemistry, I have to think about chemical things in chemistry").

3. It would be possible to investigate the extent to which the OCTET RULE FRAMEWORK is a construction of students, and to what extent is it actually *taught* in lower school classes? If it is taught by some teachers, it would be interesting to relate this to subject specialism and scientific background. (That is, for example, do physics graduates teach chemical bonding topics differently to chemistry or biology graduates.)

4. It is possible to prepare teaching schemes based upon the recommendations made in this thesis, and investigate their effectiveness in promoting more effective learning.

5. More research should be undertaken to find the extent to which both alternative frameworks, and anthropomorphic and figurative language, may act as *barriers* to the required learning, or as *bridges* between ignorance and desired learning outcomes. In particular, if alternative frameworks can take on both roles, can useful frameworks be readily distinguished from others, and their development encouraged by teachers? Work could be undertaken to investigate children and young people's use of anthropomorphic language, to find out the extent to which it is used in a poetic or teleological sense, and in particular to answer the questions:

- how aware are learners of their anthropomorphism, do they realise the implications of their language, and what do they intend such terms to convey?
- do most (all) learners pass through a 'strong (teleological) anthropomorphic' stage in understanding atomic phenomena?
- do some learners not pass beyond such a stage, being limited to understanding the atomic world in terms of the intentions and deliberate actions of atoms etc.?
- does weak (metaphorical) anthropomorphic language develop from strong (teleological) anthropomorphism, or is it a separate phenomena?

6. Research could be undertaken to find out the appropriate age to start teaching students about chemistry in terms of particle models, without requiring omissions or distortions which may hinder later learning by acting as EPISTEMOLOGICAL LEARNING IMPEDIMENTS.

7. Finally it would be possible to investigate chemistry students and prospective science teachers in higher education to find out the extent to which *octet thinking* is retained as learners become more familiar with CURRICULUM SCIENCE models and are exposed more to the quantum mechanical approach to the subject.

§12.7: Epistemological learning impediments: a personal coda.

On a personal note, I have learnt a great deal from undertaking this research. As a teacher of a particular subject at a particular level (i.e. A level chemistry) I have developed a detailed insight into the way students' ideas develop, and where they falter.

However, the most significant lesson I have learnt from this study applies to all my teaching practice - whatever the subject and level. Unlike some of those researchers and commentators cited in chapter 2 (§2.5), my research experience - sequences of in-depth interviews carried out over many months - has convinced me that that learners' alternative ideas in science can be *very stable*, and coherent enough to be effective competitors with CURRICULUM SCIENCE A learner such as Tajinder presents much more than clusters of minitheories (§2.6). Further - again unlike some of the workers cited - I am personally convinced of the reality of learners holding *multiple frameworks*, so that the student's learning of the teacher's models supplements rather than replaces any preexisting notions. In the context of my research this can not be explained in terms of different domains of knowledge (§2.7): although the OCTET RULE FRAMEWORK may be influenced by 'life-world' knowledge (such as comparisons with social actions), it is clearly an alternative abstract conceptual framework within the *scientific* domain.

In time the learning of a CURRICULUM SCIENCE model that explains more, perhaps with less arbitrary assumptions, *may* lead to a student using an alternative conception less: but when students have found their alternative schemes effective they will certainly not give them up within the time span of a few years. As *future* learning depends on *current* cognitive structure, alternative frameworks will surely have a long-term influence on a learner's thinking.

Where a student's alternative conceptions act as ONTOLOGICAL LEARNING IMPEDIMENTS the teacher has to accept and work with - or around - them. However, where alternative conceptions are EPISTEMOLOGICAL LEARNING IMPEDIMENTS they could have been avoided. Those G.C.S.E. text book authors who suggest that *chemical reactions take place so that atoms may obtain full outer shells* may feel they are simplifying a difficult and abstract topic. They may also be putting into place a learning impediment that will interfere with the students' later progression in the subject.

As a teacher I have learnt from this research that I should think very carefully before I simplify. It is never possible to tell the whole story, and in chemistry in particular our models are of limited precision and application. But I believe there is one question a teacher must try to answer about any partial explanation given:

> *is this simplification likely to provide a fertile cognitive resource for a fuller understanding, or will it be an impediment to further progression?*

If I can bear that question in mind in my professional practice, then the time and effort put into this research should pay dividends for my future students.

Understanding Chemical Bonding

The development of A level students' understanding of
the concept of chemical bonding

appendices & bibliography

Appendix 1.

Inventory of data collected.

§A1.0: Types of data collected in this study.

The research reported in the thesis was based upon a variety of data sources (see chapter 4, §4.4.2). Data was collected both from the colearners (see §4.3.2: Annie, Brian, Carol, Debra, Edward, Jagdish, Kabul, Lovesh, Mike, Noor, Paminder, Quorat, Rhea, Tajinder and Umar - students who had volunteered to attend research sessions) and from a wider sample of chemistry learners. Data collection based on planned 'interventions', such as interviews, was supplemented by the opportunistic collection of data from classroom activities that were a normal part of my teaching repertoire (see §4.2.2 and §4.10.7).

The relationship between these different slices of data is summarised in the following table (A1.1):

	colearners	other chemistry students
planned data collection	interviews dialogues construct repertory tests (§A1.1)	surveys (§A1.4)
opportunistic data collection	samples of written work (§A1.2)	samples of written work (§A1.3)

Table A1.1: data used in the research reported in this thesis

The main research technique was interviewing (see §4.6), and a schedule of the interviews analysed for the research are given below (§A1.1). A limited number of recorded colearner dialogues (see §4.8) were also analysed, as listed at the end of this section. The construct repertory test (see §4.7) was also undertaken at least once with most of the colearners, and these sessions are also listed below (§A1.1). (Details of the construct repertory test sessions are given in appendix 22.)

Another 'slice of data' considered was student course work (see §4.4.2 and §4.9). A selection of work undertaken by the colearners which was deemed relevant to the research was copied and kept on file for analysis in the research. This is inventoried in section §A1.2. This type of 'incidental' data was also collected from *other* chemistry students (see §4.10.7). Section §A1.3 provides a list of the data of this type used in the research.

Finally, two diagnostic instruments (see §4.10.8) were used to gauge the level of support for some of the ideas elicited from colearners in the research (appendices 2 and 3). The number of students surveyed are given in section §A1.4.

§A1.1: Schedule of research sessions.

Below is a schedule of the interviews analysed for this research. Each interview is given a code of the form letter-number, where the letter refers to the colearner, and the numbers are chronological. The date of the interview is given, along with the term of the students' course during which the interview occurred. The sessions when colearners responded to the construct repertory test are also listed.

Colearner A: Annie

interview code	date	term
A1	30.1.91	year 1, term 2
A2	25.6.91	year 1, term 3
A3	5.5.92	year 2, term 3
A4	19.5.92	year 2, term 3

Colearner B: Brian

interview code	date	term
B1	7.2.91	year 1, term 2
B2	14.6.91	year 1, term 3
B3	20.5.92	year 2, term 3
B4	6.7.93	(undergraduate)

construct repertory test session: 6.7.93

Colearner C: Carol

interview code	date	term
C1	18.2.91	year 1, term 2
C2	10.6.91	year 1, term 3
C3	21.5.92	year 2, term 3

Colearner D: Debra

interview code	date	term
D1	18.2.91	year 1, term 2
D2	25.9.91	year 2, term 1
D3	21.5.92	year 2, term 3

Colearner E: Edward

interview code	date	term
E1	10.6.92	year 1, term 3
E2	12.5.93	year 2, term 3

construct repertory test session: 29.10.92

Colearner J: Jagdish

interview code	date	term
J1	23.9.92	year 1, term 1
J2	10.3.93	year 1, term 2
J3	14.6.93	year 1, term 3

construct repertory test session: 04.11.92
construct repertory test session: 21.10.93
construct repertory test session: 28.10.93

Colearner K: Kabul

interview code	date	term
K1	24.9.92	year 1, term 1
K2	24.3.93	year 1, term 2
K3	26.3.93	year 1, term 2
K4	11.6.93	year 1, term 3
K5	27.1.94	year 2, term 2
K6	22.4.94	year 2, term 3

construct repertory test session: 18.11.92
construct repertory test session: 20.1.94

Colearner L: Lovesh

interview code	date	term
L1	28.9.92	year 1, term 1
L2	17.3.93	year 1, term 2
L3	16.6.93	year 1, term 3
L4	15.4.94	year 2, term 3

construct repertory test session: 27.11.92

Colearner M: Mike

interview code	date	term
M1	29.9.92	year 1, term 1
M2	10.2.93	year 1, term 2

construct repertory test session: 19.11.92

(Note: Mike gave up his studies shortly after the second interview.)

Colearner N: Noor

interview code	date	term
N1	30.9.92	year 1, term 1
N2	9.2.93	year 1, term 2
N3	18.6.93	year 1, term 3

construct repertory test session: 06.11.92
construct repertory test session: 11.11.93
construct repertory test session: 18.11.93

Colearner P: Paminder

interview code	date	term
P1	1.10.92	year 1, term 1
P2	26.1.93	year 1, term 2
P3	11.6.93	year 1, term 3

construct repertory test session: 12.11.92

Colearner Q: Quorat

interview code	date	term
Q1	7.10.92	year 1. term 1
Q2	27.1.93	year 1, term 2
Q3	10.6.93	year 1, term 3

construct repertory test session: 5.11.92

Colearner R: Rhea

interview code	date	term
R1	8.10.92	year 1. term 1

construct repertory test session: 11.11.92

(Note: Rhea gave up A level chemistry during the first year of her course.)

Colearner T: Tajinder

interview code	date	term
T1	9.10.92	year 1, term 1
T2	3.2.93	year 1, term 2
T3	21.4.93	year 1, term 3
T4	23.4.93	year 1, term 3
T5	30.4.93	year 1, term 3
T6	4.5.93	year 1, term 3
T7	11.5.93	year 1, term 3
T8	8.6.93	year 1, term 3
T9	22.6.93	year 1, term 3
T10	14.10.93	year 2, term 1
T11	18.10.93	year 2, term 1
T12	25.10.93	year 2, term 1
T13	8.11.93	year 2, term 1
T14	15.11.93	year 2, term 1
T15	23.11.93	year 2, term 1
T16	31.1.94	year 2, term 2
T17	28.2.94	year 2, term 2
T18	7.3.94	year 2, term 2
T19	11.4.94	year 2, term 3
T20	18.4.94	year 2, term 3
T21	25.4.94	year 2, term 3
T22	9.5.94	year 2, term 3
T23	16.5.94	year 2, term 3

Colearner T: Tajinder, continued.

construct repertory test session: 10.11.92
construct repertory test session: 18.05.93
construct repertory test session: 7.10.93
construct repertory test session: 24.1.94
construct repertory test session: 9.5.94

Colearner U: Umar

interview code	date	term
U1	14.9.92	year 1, term 1
U2	24.2.93	year 1, term 2
U3	10.6.93	year 1, term 3
U4	6.5.94	year 2, term 3

construct repertory test session: 25.11.92

Colearner dialogues:

code	date	term
KM1	26.2.93	year 1, term 2
QT1	21.5.93	year 1, term 3
KT1	13.12.93	year 2, term 1
JT1	2.2.94	year 2, term 2
JN1	3.2.94	year 2, term 2
LU1	10.2.94	year 2, term 2

§A1.2 Other data collected from colearners.

colearner	date	type of datum	topic
Brian	October 1991	assessment answers	multiple bonding
	May 1992	concept map	chemical bonding
Carol	October 1991	assessment answers	multiple bonding
	May 1992	concept map	chemical bonding
Debra	September 1991	concept map	chemical bonding
	October 1991	assessment answers	multiple bonding
	May 1992	concept map	chemical bonding
Edward	September 1991	concept map	chemical bonding

colearner	date	type of datum	topic
Jagdish	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	homework task	properties, structure & bonding
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	group 5
	December 1993	assessment answers	multiple bonding
	January 1994	concept map	multiple bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	concept map	energy
Kabul	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	March 1993	assessment responses	periodicity
	June 1993	concept map	s block
	June 1993	homework task	properties, structure & bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	group 5
	December 1993	assessment answers	multiple bonding
	January 1994	concept map	multiple bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	concept map	energy
Lovesh	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	January 1994	concept map	multiple bonding
	March 1994	examination question	bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	concept map	energy
Mike	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	March 1993	assessment responses	periodicity
Noor	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	January 1994	concept map	multiple bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	concept map	energy

colearner	date	type of datum	topic
Paminder	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	homework task	properties, structure & bonding
	June 1993	concept map	1st year A level chemistry
	June 1993	examination answers	selected questions
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	January 1994	concept map	multiple bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical bonding
	May 1994	concept map	energy
Quorat	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	homework task	properties, structure & bonding
	June 1993	concept map	s block
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	November 1993	concept map	group 5
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	January 1994	concept map	group 7
	May 1994	concept map	Raoult's law
Rhea	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	March 1993	assessment responses	periodicity
Tajinder	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	March 1993	assessment responses	periodicity
	June 1993	concept map	s block
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	January 1994	concept map	multiple bonding
	March 1994	revision answers	inorganic chemistry
	March 1994	examination response	bonding
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	revision answers	inorganic chemistry
	May 1994	concept map	energy
Umar	September 1992	concept map	chemical bonding
	December 1992	test responses	atomic structure & bonding
	February 1993	homework task	shells, orbitals and energy levels
	March 1993	assessment responses	periodicity
	June 1993	concept map	chemical bonding
	June 1993	examination answers	selected questions
	December 1993	assessment answers	multiple bonding
	December 1993	assessment answers	group 5
	March 1994	examination response	group 5
	May 1994	concept map	Raoult's law
	May 1994	concept map	chemical structures
	May 1994	concept map	energy

§A1.3 Incidental data collected from chemistry students.

As explained in chapter 4 (§4.4.2) 'incidental data' was collected from other chemistry students as an additional 'slice of data' to compare with the data collected from the colearners. This incidental data was collected from the context of my A level chemistry teaching. Typically this comprised of work undertaken as induction exercises at the start of the course, revision exercises, or assessment responses.

Data collected from the following sources were examined during the research:

- September 1990: first year A level students' concept maps for *chemical bonding*.
- September 1990: second year A level students' concept maps for *chemical bonding*.
- September 1991: first year A level students' concept maps for *chemical bonding*.
- September 1991: second year A level students' concept maps for *chemical bonding*.
- May 1992: second year students' concept maps for *chemical bonding*.
- September 1993: first year A level students' definitions of basic terms in chemistry (including atom, covalent bond, ionic bond), and concept maps for *chemical bonding*.
- March 1994: final year students' responses to a past examination question about bonding in sodium chloride, phosphorus (V) chloride, copper, ice and diamond in the A level mock examination.
- June 1994: first year students' responses to questions on electron affinity, atomic/ionic radii, hydrogen bonding, molecular shape, and trends in ionisation energies in their end of year examination.
- June 1994: first year students' revision concept maps on *chemical bonding*
- September 1994: first year students' concept maps for *chemical bonding*, and explanations of processes (reaction of carbon and oxygen, reaction of sodium and chlorine, dissolving of sodium chloride, dissolving and recrystallisation of sugar).
- January 1995: first year students' explanations for processes (reaction of carbon and oxygen, reaction of sodium and chlorine, dissolving of sodium chloride, dissolving and recrystallisation of sugar, reaction of sulphur and iron, reaction of ethene and bromine).
- May 1995: first year students' responses to past examination question on trends in ionisation energies.
- September 1995: first year students' definitions of basic chemical terms (including atom, molecule, ion, element, compound, valency, lattice, bond); and explanations of types of chemical bond; and explanations for why hydrogen reacts with oxygen.

- February 1996: first year students' assessment responses to past examination questions on bonding, structure and properties (in iodine, in sodium chloride, in copper); covalent bonding, water expanding on freezing, and electrical conductivity/thermionic emission in metals; trends in ionisation energies.
- September 1997: first year students' definitions of basic chemical terms (including element, compound, mixture, atom, molecule, ion, bond, chemical change, metal), and explanations of reactions (between sodium and chlorine, hydrogen and chlorine, oxygen and carbon, sodium chloride solution and silver nitrate solution).

§A1.4 Respondents to the diagnostic instruments.

THE TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT:

pilot: October 1993
first year A level group, Havering College, 15 respondents

main survey (as reported in appendix 2):

pre-A level teaching groups having studied bonding to GCSE level:
Magdalen College School, June 1994, 21 respondents
Magdalen College School, June 1994, 24 respondents
Kent College, June 1994, 11 respondents
St. Paul's Girls School, September 1994, 21 respondents
St. Paul's Girls School, September 1994, 20 respondents
St. Paul's Girls School, September 1994, 19 respondents
St. Paul's Girls School, September 1994, 19 respondents
Alleyn's School, September 1994, 20 respondents
total: 155 respondents

A level teaching groups not yet having studied bonding to A level:
Strode's College, November 1993, 20 respondents
Strode's College, November 1993, 14 respondents
St. Paul's Girls School, September 1994, 28 respondents
Havering College, September 1994, 16 respondents
Alleyn's School, September 1994, 6 respondents
total: 84 respondents

A level teaching groups having studied bonding to A level:

Strode's College, November 1993, 17 respondents
Strode's College, November 1993, 15 respondents
Havering College, December 1993, 12 respondents
Havering College, December 1993, 15 respondents
Havering College, December 1993, 15 respondents
Varndean Sixth Form College, June 1994, 9 respondents
Varndean Sixth Form College, June 1994, 10 respondents
Varndean Sixth Form College, June 1994, 7 respondents
Magdalen College School, June 1994, 15 respondents
Ashville College, July, 1994, 9 respondents
Alleyn's School, June 1994, 5 respondents

total: 129 respondent

THE TRUTH ABOUT IONISATION ENERGIES DIAGNOSTIC INSTRUMENT:

pilot: May 1994

second year A level group, Havering College, 10 respondents

respondents to main survey (as reported in appendix 3)

A level revision group, Havering College, May 1994, 13 respondents
first year A level group, Havering College, May 1994, 14 respondents
A level revision group, Havering College, May 1994, 12 respondents
A level revision group, Havering College, April 1995, 13 respondents
A level revision group, Havering College, April 1995, 11 respondents
A level revision group, Havering College, September 1995, 29 respondents
first year A level group, Havering College, May 1995, 18 respondents

total: 110 respondents

Supplementary question about chemical stability (see appendix 3, §3.6)

first year A level group, Havering College, May 1995, 16 respondents
first year A level group, Havering College, September 1995, 13 respondents

Appendix 2.

The Truth About Ionic Bonding Diagnostic Instrument.

§A2.0: Purpose of the survey.

The present survey was designed to answer the question: *is there a common alternative* 'MOLECULAR FRAMEWORK' *for understanding ionic bonding?*

Data collected in the earlier interview phase of the project suggested that a number of colearners had similar misconceptions about ionic bonding, and that these misconceptions seemed to build into a coherent alternative framework. This framework may be understood as part of the more extensive superordinate OCTET RULE FRAMEWORK (§12.3).

The MOLECULAR FRAMEWORK comprises of three aspects:-

- the VALENCY CONJECTURE: that when an ion is formed it is limited to bonding to a specific number of counter ions equal to the magnitude of its charge, e.g. the chloride ion could only form an ionic bond to *one* other ion (§11.5).
- the HISTORY CONJECTURE: that an ionic bond is formed between a cation which has donated an electron, and the *specific* anion which has accepted it (§11.4).
- the JUST FORCES CONJECTURE: that although an ion may be *attracted* to a number of counter ions larger than its valency, it is only ionically *bonded* to those counter ions which have been involved in electron transfer with it, being attracted to the other counter ions *just by forces* (§11.7).

The term MOLECULAR FRAMEWORK was chosen, as the key feature of the framework was judged to be the perceived asymmetry in the relationships between an ion in a crystal and the surrounding counter ions. Some students may actually use the term 'molecule' for groups of ions within the crystal (§11.4.3), but this was not considered as important as the asymmetry itself.

As the original work was based on a small number of students in one institution it was decided to follow-up by preparing an instrument that could be used to diagnose the extent of the MOLECULAR FRAMEWORK amongst a wider sample of chemistry learners: The TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT (TAIBDI).

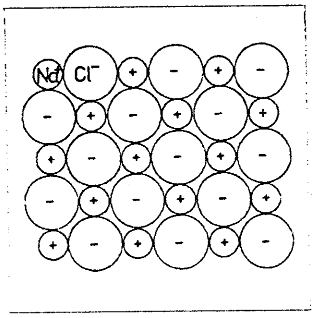
§A2.1: Characteristics of the Diagnostic Instrument.

The instrument was designed to have the following characteristics:

1) It would be a pen-and-pencil type instrument that could be administered to whole groups of students.
2) The completion and analysis of the instrument would be relatively simple.
3) It would contain sufficient items to explore aspects of the *valency*, *history* and *just forces* conjectures, and to compare the alternative MOLECULAR FRAMEWORK with the conventional basis for understanding ionic bonding (at this level taken to be an electrostatic framework).

§A2.2: The Truth About Ionic Bonding Diagnostic Instrument.

It was decided to present the original figure of ionic bonding used in the interview study (focal figure 5 from the deck of foci diagrams) showing a plane in NaCl, alongside a number of statements that might or might not be true.



focal figure 5

The respondent was asked to select 'true' or 'false' for each statement, although the option 'do not know' was available to avoid the need for a student to guess if they had no idea.

The instructions given were:

> The diagram ('figure 5') was shown to some students studying Chemistry, and they were asked to comment. The statements below are based on their replies. Please read each statement carefully, and decide whether it is correct or not. For each statement please ring one response on the answer sheet: TRUE, DO NOT KNOW or FALSE. If you are not sure whether the statement is correct or not, then ring DO NOT KNOW on the answer sheet. (Please only ring one response for each statement.)

The foci diagram had the advantage of representing:

1) an archetype ionic substance (sodium chloride) that was likely to be strongly associated with the type of bonding being considered. For example when colearners were asked to draw a representation of ionic bonding they tended to chose this example.
2) an obviously symmetrical arrangement of ions, where each ion in the body of the diagram could clearly be seen to have 4 equally nearest neighbours (in the two dimensional diagram).
3) a material where little covalent character would be expected to be introduced through polarisation of ions that could effect the symmetrical relationship between an ion and its neighbours.

In the event thirty statements were written to explore student understanding. Some were correct from the 'electrostatic' framework of CURRICULUM SCIENCE, and some correct from the various aspects of the MOLECULAR FRAMEWORK. A few items were deliberately correct or incorrect from both these perspectives. From the 'electrostatic' viewpoint there were more false statements than true ones - but this was not considered problematic (as in multiple choice questions most statements offered are incorrect). The first item was a filter designed to remove from the analysis students who did not recognise the presence of ionic bonding. Some attempt was made to randomise the presentation of other items. Some items were complementary (in that they suggested a similar idea about the cation or the anion in terms of the frameworks considered) and others were logically contradictory so that selecting TRUE for one should imply selecting FALSE for the other. The reading level of some items was recognised to be quite high, but it was felt this could not be avoided in presenting statements of this type.

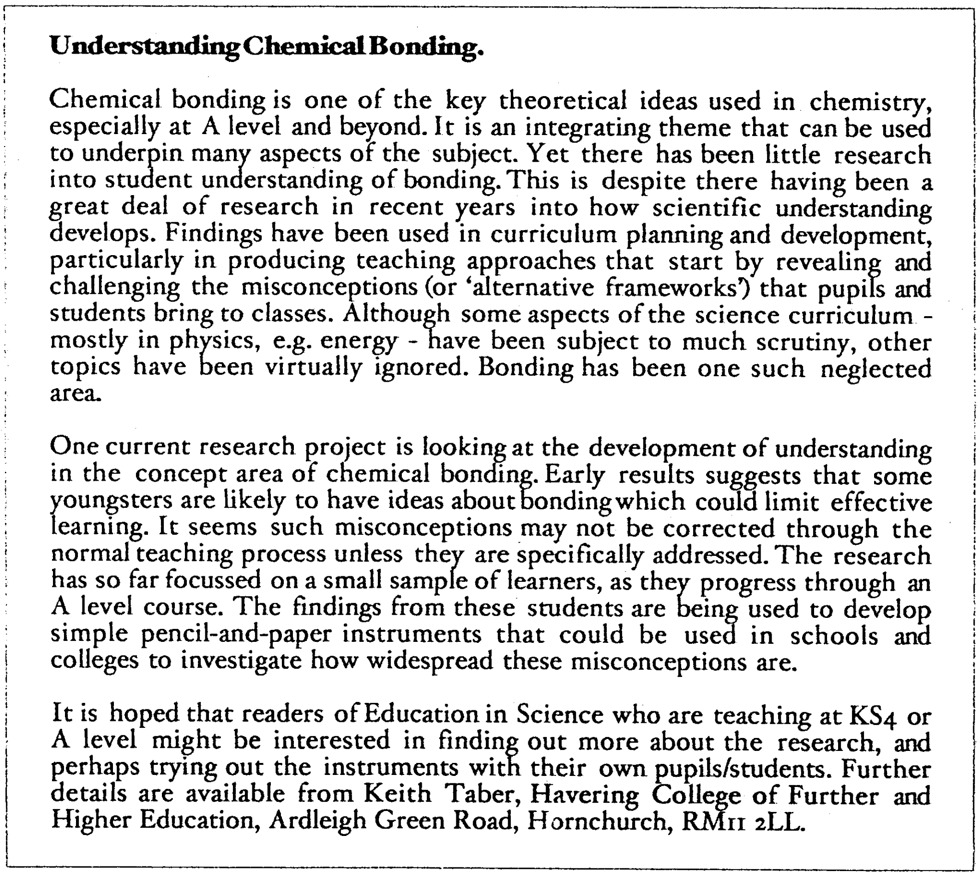
The trial. The instrument was piloted with a class at my own institution, to check that administration and analysis was straightforward. Consideration of the results led to a few minor alterations of wording, but no significant changes. The 30 items are presented in table A2.1.

item	statement
1	The diagram represents a substance with ionic bonding.
2	Each chloride ion in the diagram is bonded to only one sodium ion.
3	A sodium ion is only bonded to the chloride ion it donated its electron to.
4	A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.
5	The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.
6	In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.
7	In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion.
8	An ionic bond is the attraction between a positive ion and a negative ion.
9	A positive ion will be bonded to any neighbouring negative ions.
10	Each sodium ion in the diagram is bonded to only one chloride ion.
11	A negative ion will be attracted to any positive ion.
12	It is not possible to point to where the ionic bonds are, unless you know which chloride ions accepted electrons from which sodium ions.
13	There are exactly fifteen molecules of sodium chloride in the diagram.
14	In the diagram each chloride ion is bonded to more than one sodium ion.
15	A chloride ion is only bonded to the sodium ion it accepted an electron from.
16	Each chloride ion in the diagram is attracted to only one sodium ion.
17	A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.
18	There is a bond between the ions in each molecule, but no bonds between the molecules.
19	A negative ion can only be attracted to one positive ion.
20	The reason a bond is formed between chloride ions and sodium ions is because they have opposite charges.
21	In the diagram each sodium ion is bonded to more than one chloride ion.
22	In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.
23	A positive ion can only be attracted to one negative ion.
24	An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.
25	A negative ion will be bonded to any neighbouring positive ions.
26	There are exactly fifteen ionic bonds in the diagram.
27	There is no bonding in the diagram.
28	Each sodium ion in the diagram is attracted to only one chloride ion.
29	There are no molecules shown in the diagram.
30	A positive ion will be attracted to any negative ion.

Table A2.1: True or false?
The thirty items presented in the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT.

§A2.3: The survey.

It was not within the resources of the present project to undertake a large scale survey with a fully representative sample of chemistry learners. Instead the aim was to increase the sample size to over a hundred A level students, and to include KS4 (key stage 4 of the National Curriculum, i.e. G.C.S.E.) pupils as well if possible; and to draw the sample from several different institutions. (It was thought useful to include students taking KS4 as this is the stage immediately before A level, and therefore represents learners studying the prerequisite qualification for taking the A level course.) For this purpose a short piece was placed in *Education in Science* asking interested teachers to contact me. The text is reproduced in the box below.



Understanding Chemical Bonding.

Chemical bonding is one of the key theoretical ideas used in chemistry, especially at A level and beyond. It is an integrating theme that can be used to underpin many aspects of the subject. Yet there has been little research into student understanding of bonding. This is despite there having been a great deal of research in recent years into how scientific understanding develops. Findings have been used in curriculum planning and development, particularly in producing teaching approaches that start by revealing and challenging the misconceptions (or 'alternative frameworks') that pupils and students bring to classes. Although some aspects of the science curriculum - mostly in physics, e.g. energy - have been subject to much scrutiny, other topics have been virtually ignored. Bonding has been one such neglected area.

One current research project is looking at the development of understanding in the concept area of chemical bonding. Early results suggests that some youngsters are likely to have ideas about bonding which could limit effective learning. It seems such misconceptions may not be corrected through the normal teaching process unless they are specifically addressed. The research has so far focussed on a small sample of learners, as they progress through an A level course. The findings from these students are being used to develop simple pencil-and-paper instruments that could be used in schools and colleges to investigate how widespread these misconceptions are.

It is hoped that readers of Education in Science who are teaching at KS4 or A level might be interested in finding out more about the research, and perhaps trying out the instruments with their own pupils/students. Further details are available from Keith Taber, Havering College of Further and Higher Education, Ardleigh Green Road, Hornchurch, RM11 2LL.

It is likely that the teachers who responded are not a fair sample of those teaching chemistry nationally. Students were only included in the survey if their teachers

- read professional journals
- were interested enough to write for more information, and
- were motivated to make the effort to administer the instrument and return the responses for analysis.

It would therefore seem likely that the respondents were from classes taught by teachers who may be somewhat atypical compared to the wider population.

§A2.4: Results.

The first item, ***the diagram represents a substance with ionic bonding***, was intended to check the adequacy of the focal figure as a representation of a substance perceived to have ionic bonding, and - assuming it proved adequate - to filter out any students who did not construe it in this way. 96% of respondents thought this was true, which suggested the representation was adequate. The other 4% were excluded from the analysis of subsequent items as it was not clear they would be judging the statements against their conception (if indeed they had one) of ionic bonding.

For the subsequent items the responses were tallied in five categories:

- TRUE
- DO NOT KNOW
- FALSE
- AMBIGUOUS
- NO RESPONSE

The 'no response' category was for items for which no response was indicated by a student. Although the 'DO NOT KNOW' option was available there were some non-responses. A number of possible reasons may be conjectured. The item may have been left, then forgotten. A student may not have wanted to select an option declaring ignorance. The student may have tired of the exercise, or felt rushed if others had finished. Or the omission could be a simple mistake.

A response was classed as ambiguous if more than one of the three options appeared to have been selected. Again there could be several reasons for this: such as a change of mind where a student forgot to alter the original response, or where it was not clear which response was meant to be deleted, or a mistake where a response was entered on the wrong line (so there would be two responses for one item, and none for the previous or subsequent item.)

The number of tallies classified as either 'no response' or 'ambiguous' was a very small proportion of the total (c.1.2%), and it was judged that these responses could be ignored. Percentage response rates were therefore calculated from the unambiguous responses given. The responses were considered separately for students in the three categories:

- students studying at key stage 4 (G.C.S.E.) who had studied the topic of chemical bonding at this level.
- students studying at A level, who had not studied the topic of chemical bonding at this level, (although they had presumably studied the topic at G.C.S.E. level).
- students studying at A level, who had studied the topic of chemical bonding at this level.

For examples of the derivation of the percentage responses from the raw numbers the analysis for items 5 and 13 are presented in tables A2.2 and A2.3. The percentage responses for items 2 to 30 are presented in table A2.4.

Table A2.2: Responses to item 5
("The reason a bond is formed between chloride ions and sodium ions
is because an electron has been transferred between them.")

group	no. of 'true' responses	no. of 'do not know' responses	no. of 'false' responses	sub-total	ambiguous responses	item unanswered	total
A: KS4/GCSE (after bonding taught)	114	6	24	144	0	1	145
B: A level (before bonding taught)	63	0	17	80	0	1	81
C: A level (after bonding taught)	88	3	37	128	0	0	128

Table A2.2a: Responses to item 5

group	%age of 'true' responses	%age of 'do not know' responses	%age of 'false' responses
A: KS4/GCSE (after bonding taught)	79	4	17
B: A level (before bonding taught)	79	0	21
C: A level (after bonding taught)	69	2	29
A+B: taught to GCSE level	79	3	18
B+C: A level students	73	1	26
A+B+C: all learners	75	3	22

Table A2.2b: Percentages of (unambiguous) responses to item 5

Table A2.3: Responses to item 13
("There are exactly fifteen molecules of sodium chloride in the diagram.")

group	no of 'true' responses	no of 'do not know' responses	no of 'false' responses	sub-total	ambiguous responses	item unanswered	total
A: KS4/GCSE (after bonding taught)	111	5	28	144	0	1	145
B: A level (before bonding taught)	39	5	34	78	1	2	81
C: A level (after bonding taught)	58	13	56	127	1	0	128

Table A2.3a: Responses to item 13

group	%age of 'true' responses	%age of 'do not know' responses	%age of 'false' responses
A: KS4/GCSE (after bonding taught)	77	3	19
B: A level (before bonding taught)	50	6	44
C: A level (after bonding taught)	46	10	44
A+B: taught to GCSE level	68	5	28
B+C: A level students	47	9	44
A+B+C: all learners	60	7	34

Table A2.3b: Percentages of (unambiguous) responses to item 13

	KS4 pupils (post- teaching)		A level students (pre- teaching)		A level student (post- teaching)		results from all learners	
item	true (%)	false (%)	true (%)	false (%)	true (%)	false (%)	true (%)	false (%)
2	21	79	37	63	14	85	22	77
3	35	53	41	51	19	76	30	61
4	56	30	57	38	60	33	58	33
5	79	17	79	21	69	29	75	22
6	39	48	41	49	35	51	38	49
7	57	35	53	42	52	40	54	39
8	73	22	83	17	90	8	81	16
9	51	41	62	32	64	27	58	34
10	33	59	39	59	28	69	33	63
11	83	16	86	10	86	10	85	12
12	51	33	44	39	42	39	46	36
13	77	19	50	44	46	44	60	34
14	58	39	59	38	66	27	61	34
15	56	37	49	46	33	57	46	46
16	21	71	15	78	10	86	16	78
17	64	23	60	32	58	34	61	29
18	47	41	36	49	22	63	36	51
19	37	55	37	59	21	79	31	65
20	81	18	93	6	84	13	85	14
21	54	41	51	46	65	28	57	37
22	52	34	53	33	45	42	50	37
23	30	65	31	67	20	78	26	70
24	78	17	82.5	15	58	37	72	24
25	48	45	60	32.5	62	30	56	36
26	55	34	44	47	30	56	43	45
27	8	89	6	91	8	88	8	89
28	23	68	22.5	74	15	80	20	74
29	27	65	33	59	37	48	32	58
30	78	16	83	11	90	8	83	12

Table A2.4: Percentages of learners responding 'true' and 'false' to items 2 to 30.

(This analysis excludes respondents who answered 'false' to item one, and any ambiguous responses.)

§A2.5: Interpretation of results.

§A2.5.1: The VALENCY CONJECTURE.

The VALENCY CONJECTURE would limit sodium and chlorine to forming one ionic bond each as their ions have charge of magnitude one.

Several items related to this aspect of ionic bonding:-

2. Each chloride ion in the diagram is bonded to only one sodium ion.
4. A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.
10. Each sodium ion in the diagram is bonded to only one chloride ion.
14. In the diagram each chloride ion is bonded to more than one sodium ion.
17. A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.
21. In the diagram each sodium ion is bonded to more than one chloride ion.

Table A2.5 presents the percentage of unambiguous responses which accord with the 'molecular' interpretation for A level students before and after being taught the topic of chemical bonding,

item number	item statement	support for octet framework before teaching	support for octet framework after teaching
2	Each chloride ion in the diagram is bonded to only one sodium ion.	37% selected TRUE	14% selected TRUE
4	A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.	57% selected TRUE	60% selected TRUE
10	Each sodium ion in the diagram is bonded to only one chloride ion.	39% selected TRUE	28% selected TRUE
14	In the diagram each chloride ion is bonded to more than one sodium ion.	38% selected FALSE	27% selected FALSE
17	A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.	60% selected TRUE	58% selected TRUE
21	In the diagram each sodium ion is bonded to more than one chloride ion.	46% selected FALSE	28% selected FALSE

Table A2.5 : percentage of A level students selecting responses supporting the VALENCY CONJECTURE

Table A2.5 shows that in the sample of A level students who had not yet studied the topic of bonding at A level, the percentage of respondents selecting the option matching the VALENCY CONJECTURE varied from 37% to 60%. In the sample of A level students who had studied the topic of bonding at A level, the percentage of respondents selecting the option matching the VALENCY CONJECTURE varied from 14% to 60%.

The VALENCY CONJECTURE receives support from a significant proportion of the sample. The large variation in the support for the different items is of interest and is discussed below (§A2.5.6).

§A2.5.2: The HISTORY CONJECTURE.

The HISTORY CONJECTURE implies that in some way it matters how a particular ion came to be charged, i.e. where the parent atom donated its electron to, or accepted its electron from. An ionic bond is closely associated with the process of electron transfer and only occurs between the ions that have donated and accepted the electron.

The following items are of particular relevance.

3. A sodium ion is only bonded to the chloride ion it donated its electron to.
5. The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.
8. An ionic bond is the attraction between a positive ion and a negative ion.
12. It is not possible to point to where the ionic bonds are, unless you know which chloride ions accepted electrons from which sodium ions.
15. A chloride ion is only bonded to the sodium ion it accepted an electron from.
20. The reason a bond is formed between chloride ions and sodium ions is because they have opposite charges.
24. An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.

Table A2.6 presents the percentage of unambiguous responses which accord with the 'molecular' interpretation for A level students before and after being taught the topic of chemical bonding,

item number	item statement	support for octet framework before teaching	support for octet framework after teaching
3	A sodium ion is only bonded to the chloride ion it donated its electron to.	41% selected TRUE	19% selected TRUE
5	The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.	79% selected TRUE	69% selected TRUE
8	An ionic bond is the attraction between a positive ion and a negative ion.	17% selected FALSE	8% selected FALSE
12	It is not possible to point to where the ionic bonds are, unless you know which chloride ions accepted electrons from which sodium ions.	44% selected TRUE	42% selected TRUE
15	A chloride ion is only bonded to the sodium ion it accepted an electron from.	49% selected TRUE	33% selected TRUE
20	The reason a bond is formed between chloride ions and sodium ions is because they have opposite charges.	6% selected FALSE	13% selected FALSE
24	An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.	82.5% selected TRUE	58% selected TRUE

Table A2.6: percentage of A level students selecting responses supporting the HISTORY CONJECTURE

Table A2.6 shows that in the sample of A level students who had not yet studied the topic of bonding at A level, the percentage of respondents selecting the option matching the HISTORY CONJECTURE varied from 6% to 82.5%. In the sample of A level students who had studied the topic of bonding at A level, the percentage of respondents selecting the option matching the HISTORY CONJECTURE varied from 8% to 69%.

The HISTORY CONJECTURE receives support from a significant proportion of the sample. The large variation in the support for the different items is of interest and is discussed below (§A2.5.6).

§A2.5.3: The 'JUST FORCES' CONJECTURE.

This explains the attraction between ions that have not been involved in electron transfer as due to just forces, rather than ionic bonding.

The following items are particularly relevant:

6. In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.
9. A positive ion will be bonded to any neighbouring negative ions.
22. In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.
25. A negative ion will be bonded to any neighbouring positive ions.
26. There are exactly fifteen ionic bonds in the diagram.

Table A2.7 presents the percentage of unambiguous responses which accord with the 'molecular' interpretation for A level students before and after being taught the topic of chemical bonding.

item number	item statement	support for octet framework before teaching	support for octet framework after teaching
6	In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.	41% selected TRUE	35% selected TRUE
9	A positive ion will be bonded to any neighbouring negative ions.	32% selected FALSE	27% selected FALSE
22	In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.	53% selected TRUE	45% selected TRUE
25	A negative ion will be bonded to any neighbouring positive ions.	32.5% selected FALSE	30% selected FALSE
26	There are exactly fifteen ionic bonds in the diagram.	44% selected TRUE	30% selected TRUE

Table A2.7 : percentage of A level students selecting responses supporting the JUST FORCES CONJECTURE

Table A2.7 shows that in the sample of A level students who had not yet studied the topic of bonding at A level, the percentage of respondents selecting the option matching the JUST FORCES CONJECTURE varied from 32% to 53%. In the sample of A level students who had studied the topic of bonding at A level, the percentage of respondents selecting the option matching the JUST FORCES CONJECTURE varied from 27% to 45%.

The items attempted to distinguish between forces, and bonds. Perhaps, in view of the results from some of the items discussed above, it would have been appropriate to specify <u>ionic</u> bonds, as some students may be discriminating ionic bonds (where electron transfer has taken place) with a more general category of chemical bond based on attraction.

The JUST FORCES CONJECTURE receives support from a significant proportion of the sample. The large variation in the support for the different items is of interest and is discussed below (§A2.5.6).

§A2.5.4: The presence of molecules.

Some of the items made explicit reference to the presence of molecules in the figure:

7. In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion.
13. There are exactly fifteen molecules of sodium chloride in the diagram.
18. There is a bond between the ions in each molecule, but no bonds between the molecules.
29. There are no molecules shown in the diagram.

Table A2.8 presents the percentage of unambiguous responses which accord with the *molecular* interpretation for A level students before and after being taught the topic of chemical bonding,

item number	item statement	support for octet framework before teaching	support for octet framework after teaching
7	In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion.	53% selected TRUE	52% selected TRUE
13	There are exactly fifteen molecules of sodium chloride in the diagram.	50% selected TRUE	46% selected TRUE
18	There is a bond between the ions in each molecule, but no bonds between the molecules.	36% selected TRUE	22% selected TRUE
29	There are no molecules shown in the diagram.	59% selected FALSE	48% selected FALSE

Table A2.8 : percentage of A level students selecting responses supporting the presence of molecules in NaCl

Table A2.8 shows that in the sample of A level students who had not yet studied the topic of bonding at A level, the percentage of respondents selecting the option matching the octet framework varied from 36% to 59%. In the sample of A level students who had studied the topic of bonding at A level, the percentage of respondents selecting the option matching the octet framework interpretation varied from 22% to 52%.

The molecular model receives support from a significant proportion of the sample. The variation in the support for the different items is of interest and is discussed below (§A2.5.6).

§A2.5.5: Other items.

Seven other items were included which would not distinguish between the electrostatic and *molecular* frameworks, but could provide useful comparisons with other possible views.

One of these was *there is no bonding in the diagram* (item 27). The number of students agreeing that *there is no bonding in the diagram* was small (6% of A level students prior to studying bonding, 8%, of the sample who had studied bonding), as might be expected as the respondents had agreed that the diagram represented a substance with ionic bonding (item 1). Perhaps like one of the students (colearner Annie, see chapter 7) in the interview study they thought the figure represented 'before' bonding (maybe viewing overlap or a symbolic line as necessary for representing bonding). Alternatively, perhaps they changed their minds - or became confused - as they worked through the thirty items; or perhaps they were taking some pedantic interpretation of the meaning of the item; or maybe they were careless and misread the item.

Items concerning CURRICULUM SCIENCE **electrostatics.** The remaining six items presented statements concerning the fundamental tenet of curriculum science electrostatics, that any two opposite charges will attract each other:

11. A negative ion will be attracted to any positive ion.
16. Each chloride ion in the diagram is attracted to only one sodium ion.
19. A negative ion can only be attracted to one positive ion.
23. A positive ion can only be attracted to one negative ion.
28. Each sodium ion in the diagram is attracted to only one chloride ion.
30. A positive ion will be attracted to any negative ion.

The principle being explored here is a very basic one that should be widely known by students. It was felt important to include these items to allow respondents to demonstrate the distinction found in the interview studies between bonds and attractions. According to the JUST FORCES CONJECTURE, respondents would not always recognise a bond between ions, even when they were attracting. The table below (table A2.9) shows the percentages of respondents selecting the option which is in contradiction to this basic physical principal,

item number	item statement	support for octet framework before teaching	support for octet framework after teaching
11	A negative ion will be attracted to any positive ion.	10% selected FALSE	10% selected FALSE
16	Each chloride ion in the diagram is attracted to only one sodium ion.	15% selected TRUE	10% selected TRUE
19	A negative ion can only be attracted to one positive ion.	37% selected TRUE	21% selected TRUE
23	A positive ion can only be attracted to one negative ion.	31% selected TRUE	20% selected TRUE
28	Each sodium ion in the diagram is attracted to only one chloride ion.	22.5% selected TRUE	15% selected TRUE
30	A positive ion will be attracted to any negative ion.	11% selected FALSE	8% selected FALSE

Table A2.9 : percentage of A level students selecting responses contradicting the 'opposite charges always attract' principle.

As table A2.9 shows, the majority of respondents selected the option that was correct according to curriculum science for each of these items. However there were still significant numbers of students selecting options in contradiction to this basic electrostatic principle. Again the variations in the response patterns require further comment.

§A2.5.6: Overall response patterns.

Overall there is considerable evidence of students making responses which contradict the electrostatic model of bonding of curriculum science, but which are consistent with the alternative molecular model for ionic bonding developed from student comments in the interview studies.

However, it is important to note that the proportion of responses consistent with these two models varies considerably from item to item, so that the alternative model seems to have majority support according to some items, whereas on other items the curriculum science model appears to have overwhelming support amongst the sample. This is summarised in the table below (table A2.10),

component of model items concerning:	range of support amongst A level students prior to studying bonding (%age of unambiguous responses)	range of support amongst A level students having studied bonding (%age of unambiguous responses)
VALENCY CONJECTURE	37-60	14-60
HISTORY CONJECTURE	6-82.5	8-69
JUST FORCES CONJECTURE	32-53	27-45
presence of molecules	36-59	22-52

Table A2.10: range of support for the molecular model of ionic bonding

If all the students responding to the instrument were *either* applying the CURRICULUM SCIENCE electrostatic model, *or* the alternative molecular model of ionic bonding, then one would expect to see *similar* percentage support for the molecular model on all items in the instrument. Even if some students applied alternative frameworks which included only some of the components of the molecular model one would expect more uniformity *within* the components.

Further when the relationship between responses on closely related items are considered, a number of intriguing comparisons may be made. I will illustrate this point with a few examples of the many comparisons which may be made.

According to CURRICULUM SCIENCE, in the diagram the sodium ions were all shown to be bonded to more than one chloride ion, yet amongst the A level student yet to study bonding 46% selected FALSE to item 21. But only 39% of this group thought the sodium ions were bonded to only one chloride ion (item 10). This discrepancy *could* be reduced by allowing for the 6% of this group that thought item 27 was true: that there was no bonding in the diagram, however the 46% selecting FALSE to item 21 can also be compared to the 38% answering FALSE to item 14, that is disagreeing that each chloride ion is bonded to more than one sodium ion. The OCTET RULE FRAMEWORK provides no basis for this asymmetry between the case with the cations, and the case with the anions.

Moreover, there are other examples of this type of asymmetry. So, for example, amongst the A level students who had studied the topic of chemical bonding at A level only 19% apparently believed that a sodium ion is only bonded to the chloride ion it donated its electron to (item 3), yet 33% of this group agreed that a chloride ion is only bonded to the sodium ion it accepted an electron from (item 15). Again, nothing in the molecular model explains this, and this type of asymmetry did not arise in the interview study.

As a final example of the difficulty in interpreting the results 31% of the students yet to study the bonding topic agreed that a positive ion can only be attracted to one negative ion (item 23), yet 83% of this group agreed that a positive ion will be attracted to any negative ion (item 30), so that at least 14% of these students agreed with two contradictory statements. Again, there are other examples of contrary responses in the results.

The level of variation found in this small scale survey suggests that it is ***not*** appropriate to represent student understanding of the ionic bond as some students holding an electrostatic model, and others holding a molecular model. Such patterns in the results bring the validity of the instrument into question. However, the results may be explained on the assumption that many of the students completing the instrument held *multiple frameworks* for understanding ionic bonding, and different questions triggered application of different frameworks. This would be likely to lead to two effects:

- responses of TRUE being made for contradictory statements where both are correct according to the different frameworks held,
- responses being in part a function of item order, as each item would be read in the context of having answered the previous items.

Judging the truth of statements according to multiple frameworks could explain, for example, some students agreeing with both item 23 (true from an OCTET RULE FRAMEWORK), and item 30 (true from an electrostatic framework).

The suggestion that students may be applying multiple frameworks is not a *post hoc* assumption, as the interview study provides considerable evidence of the same phenomenon.

A related difficulty is the precise relationship students perceive between words that have similar meanings from the curriculum science perspective. For example, from an electrostatic framework the interactions between ions in sodium chloride could be referred to as bonds, *or* forces *or* attractions. From the MOLECULAR FRAMEWORK there is a distinction between these interactions (i.e. the JUST FORCES CONJECTURE), although the terms used to make the distinction may vary between students assumed to be working from the framework. In writing the instrument it was assumed that the distinction would be between:

ionic bonds / bond / chemical bonds
for intramolecular interactions between ions which had been involved in the transfer of electrons

and

attractions / forces / electrostatic forces
for inter-molecular interactions between other combinations of ions.

The pattern of responses to some of the items discussed above suggests that perhaps some students may draw the distinction in a different place, so that 'ionic bond' and 'bond' are not seen as synonymous in this context for instance. (Indeed evidence presented elsewhere has suggested that some students consider NaCl to contain ionic bonds and covalent bonds, e.g. colearner Kabul, see chapter 11, §11.4.3.)

§A2.5.7: Evidence of progression?

For the purpose of analysis the sample was divided into three groups:

A: pupils working at Key Sage 4 (GCSE) who had studied bonding
B: A level students not yet having studied bonding at A level
C: A level students who have studied boding at A level

One might expect that group B (being more mature, and more selective) would show evidence of progression over group A, and group C would certainly be expected to show progression over group B! However the sample size is limited, and it was not possible to attempt to match the respondents in the 3 groups. For this reason it is important not to over-interpret any changes in the response patterns between the three groups. Again, for this reason comments are only made where the differences seem large enough to be worthy of discussion. Statistical tests can determine when there is a significant difference in response rates - for some chosen level of confidence - but cannot determine whether this is due to the known difference between the three groups (i.e. the classification into three groups according to level of study) or various other factors (the different institutional make up of the three groups). Table A2.4 above shows that for many items the response patterns were remarkably similar over the three groups (e.g. items 4, 5, 6, 7, 11, 27).

The number of respondents agreeing that *a sodium ion is only bonded to the chloride ion it donated its electron to* fell from 37% to 19% comparing students before and after A level instruction in bonding, and there was a parallel change in those agreeing that *a chloride ion is only bonded to the sodium ion it accepted an electron from* - from 54% to 33%.

There was a large drop in the number of respondents agreeing that "there are exactly fifteen molecules of sodium chloride in the diagram" from 77% in the KS4 group to 47% amongst the A level respondents, and the number agreeing that *there are exactly fifteen ionic bonds in the diagram* fell from 55% amongst the KS4 respondents, to 30% amongst those having been taught about bonding at A level. The number agreeing that *there is a bond between the ions in each molecule, but no bonds between the molecules* dropped from 47% in the KS4 group, top 28% in the A level students, 22% in those having been taught about bonding at A level.

Although the majority of respondents in all three groups agreed that *an ionic bond is when one atom donates an electron to another atom, so that they have full outer shells* this was less popular in those having been taught bonding at A level (58%) than those who had not (79%).

§A2.6: Discussion of findings.

The statements used as the thirty items in the instrument were prepared on the basis of two possible frameworks for understanding ionic bonding: the conventional 'electrostatic' view of orthodox science, and the 'molecular' framework built from the similar comments elicited from a small group of students during individual interviews.

A framework is a complex of related ideas about a topic. Interview studies allow researchers to probe the learner's frameworks by in-depth questioning', in particular by returning to unclear, or apparently ambiguous or contradictory remarks. The type of pencil-and-paper instrument considered here does not allow this type of interrogation of the respondents' ideas - but it can explore how widely specific conceptions are held.

In principle there can be as many frameworks for conceptualising ionic bonding (or any other concept) as there are people who hold such a concept in cognitive structure. The particular differences between individuals' frameworks for a topic may be considered more or less significant. The MOLECULAR FRAMEWORK for ionic bonding being considered is an amalgam of ideas elicited from several individual learners, as interpreted by one researcher (see the discussion of what is meant by a framework in chapter 2, §2.4). It was never expected that students responding to the instrument would answer all items consistently according to either the *molecular* or *electrostatic* frameworks. Rather, it was expected that, for example, some might apply the tenet of the VALENCY CONJECTURE, but not the HISTORY CONJECTURE, and that some might apply molecular ideas whilst rejecting the items referring explicitly to molecules. In practice the results are more complicated than this, with items that apparently test the same basic idea responded to in different ways by considerable numbers of students.

Such apparent inconsistency in the responses of any one individual might suggest confusion and an element of guessing. However experience from interview studies suggests that apparent confused and inconsistent statements may on further probing shift into a perfectly consistent view of the world, once the researcher realises the precise meanings the learner gives to the words used. In a moderately large sample 'guessing' would be expected to produce a randomisation of responses, and would make large asymmetries between equivalent statements for the anions and cations unlikely in the absence of some other effect.

§2.7: Conclusions.

In this survey of approximately 350 pupils/students studying chemistry the alternative conceptions about ionic bonding revealed in the interview study were found to be shared by a considerable proportion of the respondents.

Most of the students thought that sodium and chlorine were only capable of forming one ionic bond each. Although most respondents thought that the ionic bond was an electrostatic attraction between oppositely charged ions, they also - mostly - failed to distinguish between the actual ionic bond, and the process of electron transfer. Half the respondents thought that the interactions between a sodium ion and its surrounding counter ions were of two types, a bond with one, and just forces with the others. Most of the students thought the diagram showed substances that contained molecules of one sodium ion and one chloride ion. Although not all items distinguishing between the 'molecular' and 'electrostatic' interpretations were selected by the majority of respondents, the 'molecular' interpretation was always selected by substantial numbers of pupils. When comparisons are made between KS4 pupils and A level students, or between A level students before and after being taught about bonding, the level of support for alternative conceptions sometimes fell: but on many items it did not.

The TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT does seem to have the potential to allow teachers to identify the alternative conceptions uncovered in the interview study. In view of the complexity of the response patterns uncovered the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT may need further development work. However it may be used either to check for the presence of common alternative conceptions (before or after teaching), or to act as an introductory exercise for the teacher to identify points of interest to discuss with individual students, or as a basis for class discussion.

Appendix 3.

The Truth About Ionisation Energy Diagnostic Instrument.

§A3.0: The purpose of the survey.

The truth about ionisation energy diagnostic instrument was designed to test the generalisability of some of the alternative conceptions elicited during the interview study.

§A3.1: The diagnostic instrument.

The focal figure for this instrument was focal figure 1 from the interview study, showing an atom with sodium electronic configuration in terms of shells.

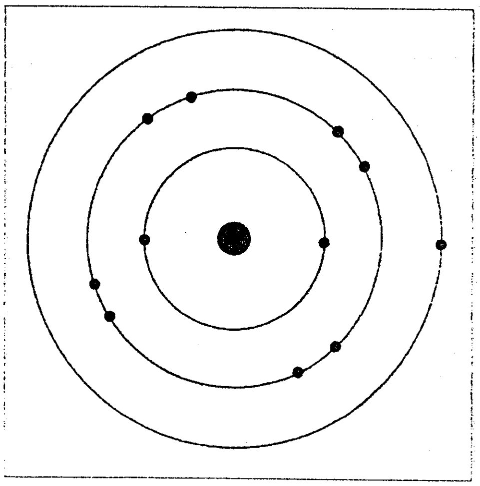


figure presented for the T.A.I.E.D.I. instrument (focal figure 1)

Thirty items were written for this instrument: they are shown in table A3.1. The items were presented in a quasi-random order, but may be grouped into four subsets. The statements were written to reflect four explanatory principles, that my research suggests students *may* apply. Two of these were from CURRICULUM SCIENCE (Newton's third law, where colearners had made many 'errors' in the interviews, and Coulomb's law, see §10.4) and two were alternative conceptions uncovered in the enquiry as presented earlier: CONSERVATION OF FORCE (§10.5), and the OCTET RULE EXPLANATORY PRINCIPLE (§11.2).

	item
1	The force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron.
2	After the atom is ionised, it then requires more energy to remove a second electron because the second electron is nearer the nucleus.
3	All electrons are attracted to the nucleus equally.
4	Each proton in the nucleus attracts one electron.
5	The atom would be more stable if it 'lost' an electron.
6	Energy is required to remove an electron from the atom.
7	If one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus.
8	The nucleus is not attracted to the electrons.
9	After the atom is ionised, it then requires more energy to remove a second electron because the second electron experiences less shielding from the nucleus.
10	The force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron.
11	The atom will spontaneously lose an electron to become stable.
12	Only one electron can be removed from the atom, as it then has a stable electronic configuration.
13	The eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons.
14	The force on an innermost electron from the nucleus is equal to the force on the nucleus from an innermost electron.
15	Electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons.
16	After the atom is ionised, it then requires more energy to remove a second electron because the second electron is in a lower energy level.
17	Each proton in the nucleus attracts all the electrons.
18	The atom would become stable if it either lost one electron or gained seven electrons.
19	The force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed.
20	After the atom is ionised, it then requires more energy to remove a second electron because it would be removed from a positive species.
21	The third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus.
22	The force pulling the outermost electron towards the nucleus is smaller than the force pulling the nucleus towards the outermost electron.
23	The force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed.
24	After the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus.
25	The nucleus is attracted towards the outermost electron less than it is attracted towards the other electrons.
26	The atom would be less stable if it 'lost' an electron.
27	The force on an innermost electron from the nucleus is less than the force on the nucleus from an innermost electron.
28	After the atom is ionised, it then requires more energy to remove a second electron because it experiences a greater core charge than the first.
29	The force pulling the outermost electron towards the nucleus is equal to the force pulling the nucleus towards the outermost electron.
30	If the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration.

Table A3.1: the items used in the TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT

Some of the items are relevant to more than one of these themes, but the items could be grouped according to the following scheme:

- Coulombic framework. Some of the items were designed to see if A level chemistry students used the explanations given in CURRICULUM SCIENCE These items were numbers 2, 9, 16, 20, 23, 25, 26 and 28.
- Newton-3. Some of the items were designed to see if A level chemistry students applied Newton's third law in the context of an atomic structure. These items were numbers 1, 8, 10, 14, 15 , 22, 27 and 29.
- Conservation of force. Some of the items were designed to see if A level chemistry students would agree with statements based on the CONSERVATION OF FORCE CONCEPTION. These items were numbers 3, 4, 7, 13, 18, 21, and 24.
- The OCTET RULE FRAMEWORK (see chapter 12, §12.3) definition of stability. Some of the items were designed to see if students would consider 'octet' configurations as more stable than the atomic configuration in the absence of explicit mention of bond formation. These items were numbers 5, 6, 11, 12 and 30.

The items included in the instrument. The choice of the thirty statements was based around my perception of the truth value of each of the statements from the perspective of one or more of the four explanatory principles. The validity of the items depends on this relationship, and therefore it is appropriate to explain the items:

- Item 1. The statement, "the force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron", contravenes Newton's 3rd law (and Coulomb's law) and therefore is FALSE from a CURRICULUM SCIENCE perspective.
- Item 2. The statement "after the atom is ionised, it then requires more energy to remove a second electron because the second electron is nearer the nucleus" has two components. Assuming that the student is aware that the outermost electron will be removed first during successive ionisation, the truth of the reason (*the second electron is nearer the nucleus*) may be checked from the diagram, by observation. Therefore the force acting on the second electron will be greater, and more work has to be done to remove it from the atom, so the statement is TRUE.
- Item 3. The statement "all electrons are attracted to the nucleus equally" is clearly FALSE from Coulomb's law as the diagram shows the distances from the nucleus to vary. However one interpretation of the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE could take the form that each electron is attracted to the nucleus by the same force, i.e. 'one proton's worth' of force.
- Item 4. Similarly the statement "each proton in the nucleus attracts one electron" may follow for some students holding a CONSERVATION OF FORCE CONCEPTION

although it is FALSE from the Coulombic framework.

- Item 5. The statement "the atom would be more stable if it 'lost' an electron" would appear to be absolutely TRUE from an OCTET RULE FRAMEWORK, but from a CURRICULUM SCIENCE perspective the precise comparison would need to be more clearly defined before a definitive judgment of the statement could be made. In terms of the scenario which would seem to be implied (Na^+ ion and separated electron, compared to Na atom), the statement is FALSE.
- Item 6. The statement "energy is required to remove an electron from the atom" is clearly TRUE from a CURRICULUM SCIENCE perspective as the positive core attracts the electron, and (from this viewpoint) is contrary to the statement of item 5. Any student who has studied ionisation energies would be expected to recognise the truth of this statement, and therefore it was considered to be a useful statement to compare with item 5.
- Item 7. The statement "if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus" follows as TRUE from the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE, but is clearly FALSE from CURRICULUM SCIENCE as no accepted scientific principle would lead to this deduction.
- Item 8. The statement "the nucleus is not attracted to the electrons", is FALSE as the opposite follows from the correct interpretation of Coulomb's law. Given that it is accepted that the electrons are attracted to the nucleus, then this statement is a NEWTON-3 ERROR.
- Item 9. The statement "after the atom is ionised, it then requires more energy to remove a second electron because the second electron experiences less shielding from the nucleus" is TRUE from the Coulombic model, as the core charge increases from +1 to +9.
- Item 10. The statement "the force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron" is FALSE from the CURRICULUM SCIENCE perspective and would be classed as an example of a NEWTON-3 ERROR.
- Item 11. The statement "the atom will spontaneously lose an electron to become stable" should be clearly FALSE to A level students who had studied the topic of ionisation energy - the energy required to remove electrons from atoms. However, the statement could be a possible TRUE deduction from some interpretations of the consequences of the FULL SHELLS EXPLANATORY PRINCIPLE.
- Item 12. The statement "only one electron can be removed from the atom, as it then has a stable electronic configuration" should appear as clearly FALSE to students who have studied the patterns in successive ionisation energies. However, as with the previous item, the statement could be a possible TRUE

deduction from some interpretations of the consequences of the FULL SHELLS EXPLANATORY PRINCIPLE

- Item 13. The statement "the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons" is TRUE according to the CONSERVATION OF FORCE CONCEPTION, but is FALSE according to the Coulombic framework - where the force between two bodies depends on the product of their two charges, without regard to what other charges might be interacting. (In CURRICULUM SCIENCE the forces due to different interactions are calculated independently, and then a net force may be found, except where the procedure may be simplified, e.g. by using core charge.)
- Item 14. The statement "the force on an innermost electron from the nucleus is equal to the force on the nucleus from an innermost electron" must be TRUE according to Newton's third law.
- Item 15. The statement "electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons" is FALSE as it makes two separate NEWTON-3 ERRORS: that the action-reaction force for an attraction could be a repulsion, and that forces acting on *different* bodies might cancel.
- Item 16. The statement "after the atom is ionised, it then requires more energy to remove a second electron because the second electron is in a lower energy level" is TRUE from the CURRICULUM SCIENCE perspective. (Students should 'know' that the 2p level is lower in energy than 3s, and from the Coulombic model it can be seen why a second shell electron has a lower potential energy.)
- Item 17. The statement "each proton in the nucleus attracts all the electrons" is TRUE from a CURRICULUM SCIENCE perspective as protons are positive and electrons are negative (although a possible interpretation of the CONSERVATION OF CHARGE EXPLANATORY PRINCIPLE may suggest the statement is FALSE: c.f. item 4).
- Item 18. The statement "the atom would become stable if it either lost one electron or gained seven electrons" is FALSE from the CURRICULUM SCIENCE perspective, in particular because of the charge concentration on an Na^{7-} species, although it could be a TRUE consequence of the FULL SHELLS EXPLANATORY PRINCIPLE, as it would have an electronic configuration of 2.8.8. (It should be noted that the use of the word "or" in the statement could be seen as ambiguous, and this is discussed below.)
- Item 19. The statement "the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed" is FALSE from an electrostatic model (as if the outer shell electrons had any effect on the inner shell electrons it would be to

repel them towards the nucleus, where they would experience greater attraction, so the removal of these electrons would lead to a greater radius and less force towards the nucleus). However, according to the CONSERVATION OF FORCE CONCEPTION the two electrons will experience a greater share of the nucleus' force if the outer shells are removed, and the statement is TRUE.

- Item 20. The statement "after the atom is ionised, it then requires more energy to remove a second electron because it would be removed from a positive species" is TRUE from the Coulombic framework, as the first electron is removed from a core of fixed charge +1, but the second electron is removed from a species that has an overall charge of +2 (once the electron can be considered 'outside' the atom: initially it is acted by the core of charge +9).
- Item 21. The statement "the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus" is FALSE from the Coulombic model, the correct reason being the reduced repulsion between electrons in the shell leads to an average nucleus-electron separation which is smaller at equilibrium. However, the CONSERVATION OF FORCE CONCEPTION implies that the statement is TRUE.
- Item 22. The statement "the force pulling the outermost electron towards the nucleus is smaller than the force pulling the nucleus towards the outermost electron" is FALSE from the CURRICULUM SCIENCE perspective, and is an example of a NEWTON-3 ERROR.
- Item 23. The statement "the force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed" would be FALSE if interpreted using the CONSERVATION OF FORCE CONCEPTION, but (see item 19) could be considered TRUE from a 'first order' interpretation of the Coulombic model: i.e. in both systems there are 2 electrons in the shell, and they are attracted by a charge of +11.
- Item 24. The statement "after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus" gives a FALSE reason from the Coulombic model, but would be TRUE according to the alternative CONSERVATION OF FORCE CONCEPTION.
- Item 25. The statement "the nucleus is attracted towards the outermost electron less than it is attracted towards the other electrons" is TRUE from the Coulombic model of CURRICULUM SCIENCE as the nucleus-electron separation is larger than for the other electrons.
- Item 26. The statement "the atom would be less stable if it 'lost' an electron", is TRUE from the CURRICULUM SCIENCE perspective as the electron is attracted to the atomic core and work must be done to remove it, but may be seen as FALSE from the OCTET RULE FRAMEWORK where stability is defined in terms of full outer shells.

- Item 27. The statement "the force on an innermost electron from the nucleus is less than the force on the nucleus from an innermost electron" is FALSE from the CURRICULUM SCIENCE perspective, and would be an example of a NEWTON-3 ERROR.
- Item 28. The statement "after the atom is ionised, it then requires more energy to remove a second electron because it experiences a greater core charge than the first" is TRUE from a CURRICULUM SCIENCE perspective as after ionisation the force is acting between charges of -1 and +9, rather than -1 and +1.
- Item 29. The statement "the force pulling the outermost electron towards the nucleus is equal to the force pulling the nucleus towards the outermost electron" is TRUE from a CURRICULUM SCIENCE perspective where force is considered to act between two bodies.
- Item 30. The statement "if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration" is FALSE from the CURRICULUM SCIENCE perspective as there will be an attractive force between the electron and cation, but may appear TRUE from the perspective of the OCTET RULE FRAMEWORK as the cation will be seen as a stable entity. (This item may be answered as TRUE, because the separated electron may be seen as unstable, or even impossible.)

The format of the instrument was the same as for the TRUTH ABOUT IONIC BONDING DIAGNOSTIC INSTRUMENT (see appendix 2): each student was provided with the focal diagram, the list of thirty numbered statements, and a response sheet with the three options 'TRUE', "DO NOT KNOW' and 'FALSE' by each of the numbers 1 to 30. The instructions invited the student to decide if each item statement was 'true' or 'false':

> "The statements refer to the diagram of an atom. Please read each statement carefully, and decide whether it is correct or not. For each statement please ring one response: TRUE, DO NOT KNOW or FALSE".

§A3.2: The pilot.

The instrument was piloted during a normal class session (18.5.94), with the second year A level group that included the colearners in the main study (i.e. Tajinder's cohort). Ten students were present, including seven of the co-learners. There were no difficulties in administering the instrument. The results of the pilot are presented in table A3.2.

item	'TRUE'	'DO NOT KNOW'	'FALSE'	sub-total	ambiguous	no response	total
1	2	0	8	10	0	0	10
2	10	0	0	10	0	0	10
3	1	0	8	9	0	1	10
4	0	0	10	10	0	0	10
5	10	0	0	10	0	0	10
6	10	0	0	10	0	0	10
7	4	2	3	9	0	1	10
8	1	0	9	10	0	0	10
9	8	0	1	9	0	1	10
10	3	0	6	9	0	1	10
11	6	0	4	10	0	0	10
12	1	0	9	10	0	0	10
13	6	1	2	9	0	1	10
14	8	0	0	8	0	2	10
15	5	0	3	8	0	2	10
16	8	0	0	8	0	2	10
17	9	0	1	10	0	0	10
18	10	0	0	10	0	0	10
19	5	0	4	9	0	1	10
20	8	0	1	9	0	1	10
21	7	0	1	8	0	2	10
22	0	0	8	8	0	2	10
23	3	0	5	8	0	2	10
24	6	0	1	7	1	2	10
25	5	0	4	9	0	1	10
26	0	0	10	10	0	0	10
27	0	0	9	9	0	1	10
28	9	0	0	9	0	1	10
29	9	0	0	9	0	1	10
30	6	0	3	9	0	1	10

Table A3.2: results from pilot of T.A.I.E.D.I.

The pilot demonstrated that on some items responses were selected that were inappropriate from a CURRICULUM SCIENCE perspective. This might be expected as the group included some of the colearners who had offered evidence of the alternative conceptions on which the items were based - although as the instrument was used at the *end* of the course this is still disappointing from a pedagogic perspective.

Although most of the statements written about NEWTON-3 ERRORS were generally answered according to the CURRICULUM SCIENCE perspective, five of the respondents thought that the statement "electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons" (item 15) was TRUE.

All ten respondents thought that the statement "the atom would be more stable if it 'lost' an electron" (item 5) was TRUE. Six of the respondents thought that the statement "the atom will spontaneously lose an electron to become stable" (item 11) was TRUE. All ten of the respondents thought that the statement "the atom would become stable if it either lost one electron or gained seven electrons" was TRUE, and that the statement "the atom would be less stable if it 'lost' an electron" (item 26) was FALSE. Six of the respondents thought the statement "if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration" was TRUE. These responses all suggest that thinking according to an OCTET RULE FRAMEWORK (chapter 11) was common when considering about the statements.

Four of the respondents thought the statement "if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus" (item 7) was TRUE. Six of the respondents thought that the statement "the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons" (item 13) was TRUE. Five of the respondents thought the statement "the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed" (item 19) was TRUE; and five thought the statement "the force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed" (item 23) was FALSE. Seven of the respondents thought the statement "the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus" (item 21) was TRUE; and six of the respondents thought that the statement "after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus" (item 24) was TRUE. This suggests that thinking based on the CONSERVATION OF FORCE CONCEPTION was widely used by the respondents.

After the pilot the group was given feedback about their responses compared with those expected from CURRICULUM SCIENCE I noted colearner Paminder's comment that,

> "I can't think about physics in chemistry, I have to think about chemical things in chemistry."
> (Paminder, 25.5.94)

§A3.3: Results from a sample of chemistry learners.

The instrument was then used with a number of other chemistry classes. All these classes were taking place at my own institution. Two groups (taking the instrument in May 1994, and May 1995) were first year classes that had studied the topic of ionisation energies. The other students (who took the instrument in May 1994, April 1995, and September 1995) were from five classes of revision students , i.e. students taking a one year A level re-take course.

Taken together over one hundred students responded to each of the items. These students do not make up a representative sample and some of the revision students, but not others, took the instrument after they had repeated the topic during their revision course. However this number of students does give an indication of whether the items in the instrument are suitable for diagnosing the relevant alternative conceptions. The results are given in table A3.3.

item	'TRUE'	'DO NOT KNOW'	'FALSE'	sub-total	ambiguous	no response	total
1	58 (53%)	5 (5%)	46 (42%)	109	0	1	110
2	98 (89%)	1 (1%)	11 (10%)	110	0	0	110
3	15 (14%)	3 (3%)	91 (83%)	109	1	0	110
4	37 (34%)	4 (4%)	67 (62%)	108	0	2	110
5	83 (75%)	4 (4%)	23 (21%)	110	0	0	110
6	108 (99%)	0 (0%)	1 (1%)	109	1	0	110
7	72 (69%)	7 (7%)	26 (25%)	105	0	5	110
8	14 (13%)	6 (6%)	87 (81%)	107	1	2	110
9	62 (57%)	3 (3%)	43 (40%)	108	0	2	110
10	45 (41%)	11 (10%)	53 (49%)	109	0	1	110
11	30 (28%)	4 (4%)	73 (68%)	107	0	3	110
12	38 (35%)	2 (2%)	69 (63%)	109	0	1	110
13	76 (72%)	10 (9%)	20 (19%)	106	0	4	110
14	57 (53%)	13 (12%)	38 (35%)	108	0	2	110
15	65 (60%)	16 (15%)	27 (25%)	108	0	2	110
16	54 (50%)	4 (4%)	50 (46%)	108	0	2	110
17	70 (64%)	10 (9%)	30 (27%)	110	0	0	110
18	91 (83%)	3 (3%)	16 (15%)	110	0	0	110
19	81 (74%)	4 (4%)	24 (22%)	109	1	0	110
20	68 (63%)	9 (8%)	31 (29%)	108	0	2	110
21	77 (70%)	5 (5%)	28 (25%)	110	0	0	110
22	22 (21%)	12 (11%)	72 (68%)	106	0	4	110
23	28 (25%)	7 (6%)	75 (68%)	110	0	0	110
24	85 (79%)	6 (6%)	16 (15%)	107	0	3	110
25	81 (74%)	1 (1%)	28 (25%)	110	0	0	110
26	14 (13%)	7 (6%)	89 (81%)	110	0	0	110
27	16 (15%)	15 (14%)	75 (71%)	106	0	4	110
28	75 (68%)	11(10%)	24 (22%)	110	0	0	110
29	71 (65%)	6 (6%)	32 (29%)	109	0	1	110
30	62 (56%)	12 (11%)	36 (33%)	110	0	0	110

Table A3.3: Results from the T.A.I.E.D.I..

§A3.4: Interpretation of results.

§A3.4.1: Newton-3.

Some of the items were designed to see if A level chemistry students applied Newton's third law in the context of an atomic structure.

53% of the respondents made the NEWTON-3 ERROR of agreeing that "the force on an innermost electron from the nucleus is greater than the force on the nucleus from an innermost electron" (item 1), and 41% agreed that "the force pulling the outermost electron towards the nucleus is greater than the force pulling the nucleus towards the outermost electron" (item 10). 35% of the respondents thought the statement "the force on an innermost electron from the nucleus is equal to the force on the nucleus from an innermost electron" (item 14) was FALSE. Smaller proportions of the respondents made NEWTON-3 ERRORS in answering items 22, 27 and 29, but all of these items found some support for the alternative belief.

Perhaps most significantly, 60% of respondents agreed that "electrons do not fall into the nucleus as the force attracting the electrons towards the nucleus is balanced by the force repelling the nucleus from the electrons" (item 15), a statement which incorporated two 'errors'.

§A3.4.2: Conservation of charge.

The statement "each proton in the nucleus attracts all the electrons" (item 17) is based on a premise of CURRICULUM SCIENCE, that any positive charge will attract any negative charge. Although 64% of respondents thought the statement was TRUE, 27% thought it was FALSE. A similar proportion, 34%, of respondents to item 4 agreed that "each proton in the nucleus attracts one electron".

Most of the respondents, 72%, thought that the statement most closely based on the CONSERVATION OF FORCE CONCEPTION, "the eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons" (item 13) was TRUE, with only 19% claiming it was FALSE. Almost as many, 69% of respondents, agreed that "if one electron was removed from the atom the other electrons will each receive part of its attraction from the nucleus" (item 7). A similar proportion, 70%, agreed that "the third ionisation energy is greater than the second as there are less electrons in the shell to share the attraction from the nucleus" (item 21), and an even greater proportion, 79%, agreed that "after the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus" (item 24). 74% of respondents thought the statement "the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed" (item 19) was TRUE, and the statement "the force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed" (item 23) was thought to be FALSE by 68% of those responding.

Statements developed from the CONSERVATION OF FORCE CONCEPTION were therefore thought to be true by a substantial majority of this sample of students, and as this conception contradicts CURRICULUM SCIENCE this is thought to be a significant finding.

§A3.4.3: Octet rule definition of stability.

75% of respondents agreed that "the atom would be more stable if it 'lost' an electron" (item 5), and 81% thought the statement "the atom would be less stable if it 'lost' an electron" (item 26) was FALSE.

Despite this only 28% of respondents thought that "the atom will spontaneously lose an electron to become stable" (item 11), and 99% of respondents knew that "energy is required to remove an electron from the atom" (item 6). 56% of respondents agreed that "if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration" (item 30), despite the near unanimous acknowledgement that energy is needed to remove the electron. It would seem that most of the students were interpreting the term 'stable' from within their OCTET RULE FRAMEWORKs, but answering items that did not specifically use this word from their learning of CURRICULUM SCIENCE.

35% of respondents thought that "only one electron can be removed from the atom, as it then has a stable electronic configuration" (item 12), despite having studied patterns in successive ionisation energies.

Finally, 83% of respondents agreed that "the atom would become stable if it either lost one electron or gained seven electrons" (item 18). If the students were interpreting the statement as intended (see below), they were overwhelmingly suggesting that not only would Na^+ (electronic configuration, 2.8) be stable, but so would the species Na^{7-} (electronic configuration, 2.8.8), which is highly unstable from a CURRICULUM SCIENCE perspective.

§A3.5: Review of the Instrument.

The instrument certainly demonstrated that although students have studied the topic of ionisation energies, they commonly accept statements based on alternative explanatory schemes: so they make NEWTON-3 ERRORS, and show acceptance of ideas based on the conservation of charge, and the octet rule definition of stability. The items used did not seem to cause the students too many problems (with at least 105/110 students making a clear response for one of the three options on each item).

In retrospect 3 of the items may be considered dubious:

- Item 9:

"*After the atom is ionised, it then requires more energy to remove a second electron because the second electron experiences less shielding from the nucleus.*"
40% of the respondents rejected this, which may reflect a genuine difficulty with the shielding concept. However the wording may have been unclear to some students, in particular "experiences less shielding from the nucleus", as it is possible this could be taken to suggest *the nucleus* provides some sort of 'shielding'. If the Instrument is to be used for diagnostic purposes, it may be necessary to lengthen the statement to ensure this is clear. For example, the following form may be clearer:
"*after the atom is ionised, it then requires more energy to remove a second electron because the second electron is shielded from the nucleus less by other electrons*"

- Item 18:

"*The atom would become stable if it either lost one electron or gained seven electrons.*"
This item was intended to reflect Annie's alternative 'deviation charge' electrostatics (see chapter 7), and it was not expected from the interview study that many students would select this. As 83% thought this was TRUE, and only 15% thought it was FALSE it is appropriate to submit the item to scrutiny.

It is possible that the 'either/or' in this item is unambiguous in that instead of being read as

> *the atom would become stable if it lost one electron, and the atom would become stable if it gained seven electrons*

it could be read as

> *the atom would become stable if it lost one electron, or the atom would become stable if it gained seven electrons gained seven electrons*

and the response TRUE might only be agreeing with one of the options.

One possible way to avoid this ambiguity is to replace or supplement it with an item statement such as:
"*the atom would be more stable if it gained seven electrons*"

However, as other items also suggested students commonly applied an OCTET RULE FRAMEWORK definition of stability, a separate specific instrument was designed - the 'chemical stability question' (see below, §A3.6).

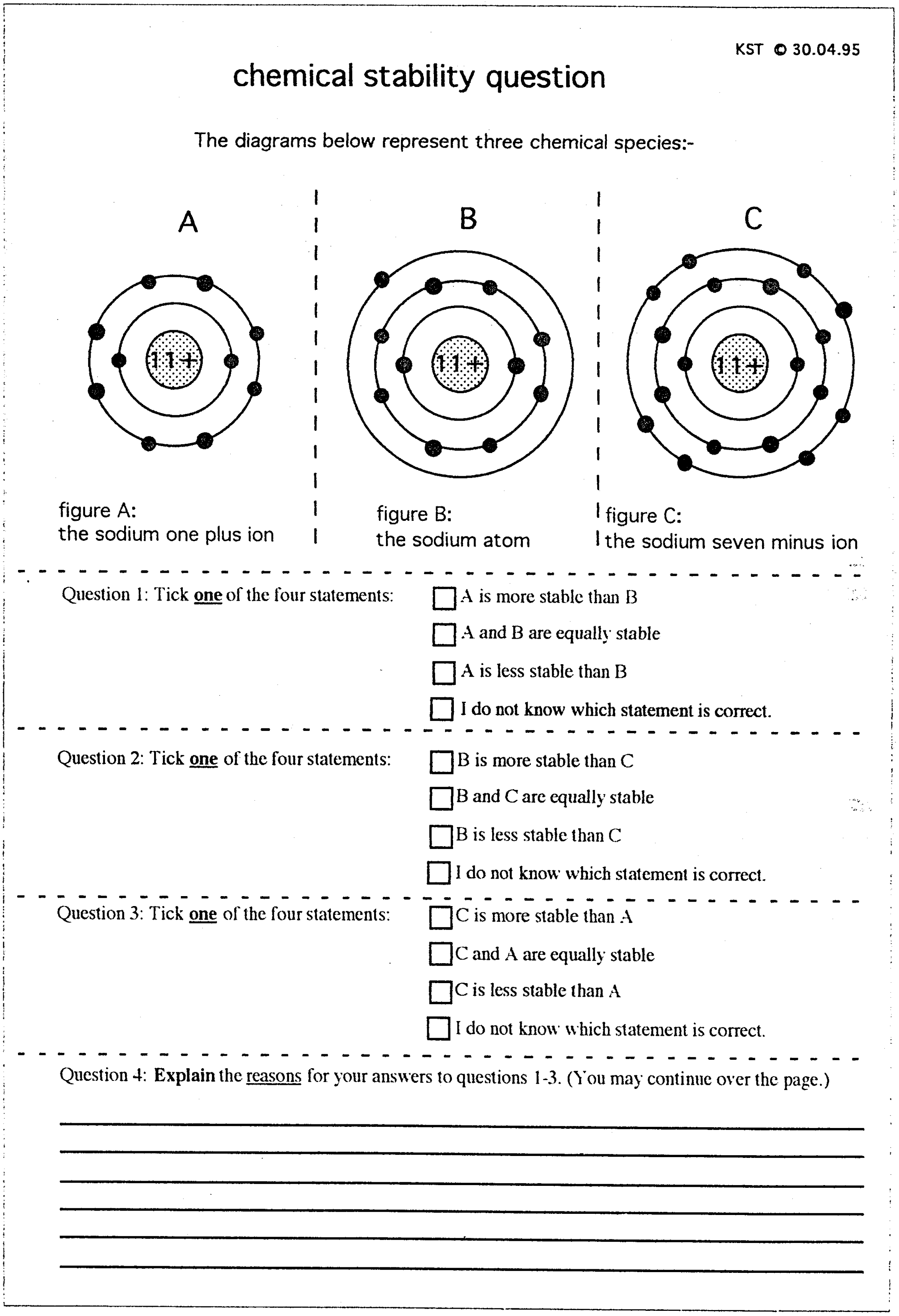
- Item 23:

"*The force attracting the electrons in the first shell towards the nucleus would not change if the other two shells of electrons were removed.*"
As was explained above, this statement is TRUE from a first order electrostatic perspective, but FALSE if an argument is developed from the CONSERVATION OF FORCE CONCEPTION However, a student could make a more sophisticated analysis using CURRICULUM SCIENCE principles, and deduce that the outer shells of electrons have an influence on the mean electron-nucleus distance through Coulombic forces. Such an analysis would suggest the inner electrons are closer to the nucleus, and attracted more strongly, when the other electrons are present. The CONSERVATION OF FORCE CONCEPTION would predict the opposite, that the inner electrons are closer to the nucleus, and attracted more strongly, when the other electrons are absent. However, this item does not distinguish between these two options.

It is suggested that this limitation would need to be borne in mind if the instrument was used for testing purposes, however the purpose of the instrument is to diagnose potential alternative conceptions, and the distinction *is* made by item 19 ("*the force attracting the electrons in the first shell towards the nucleus would be much greater if the other two shells of electrons were removed*").

§A3.6: A question about chemical stability.

A simple instrument was designed to diagnose student conceptions of chemical stability, and in particular to find the extent to which 'stability' was understood in terms of an OCTET RULE FRAMEWORK. A reduced reproduction of the question (originally on an A4 sheet) is given below (figure A3.1).



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chemical stability question

The diagrams below represent three chemical species:-

A	B	C
figure A: the sodium one plus ion	figure B: the sodium atom	figure C: the sodium seven minus ion

Question 1: Tick **one** of the four statements:

☐ A is more stable than B
☐ A and B are equally stable
☐ A is less stable than B
☐ I do not know which statement is correct.

Question 2: Tick **one** of the four statements:

☐ B is more stable than C
☐ B and C are equally stable
☐ B is less stable than C
☐ I do not know which statement is correct.

Question 3: Tick **one** of the four statements:

☐ C is more stable than A
☐ C and A are equally stable
☐ C is less stable than A
☐ I do not know which statement is correct.

Question 4: **Explain** the reasons for your answers to questions 1-3. (You may continue over the page.)

Figure A3.1: diagnostic question on chemical stability.

The instrument was used during May 1995 with a group of my first year A level students who had studied the topics of chemical bonding and ionisation energies. The instrument consisted of three objective questions and an open response section where reasons for the earlier responses were requested. The diagram showed three species: Na^{+}, Na•, Na^{7-}:

The three closed questions asked students to select one statement about the relative stability of pairs of diagrams. The results are given below in tables A3.4-6.

option selected	number selecting
A is more stable than B	13
A and B are equally stable	2
A is less stable than B	1
I do not know which statement is correct	0
total	16

Table A3.4: relative stability of Na^{+} and Na•

option selected	number selecting
B is more stable than C	6
B and C are equally stable	0
B is less stable than C	10
I do not know which statement is correct	0
total	16

Table A3.5 relative stability of Na• and Na^{7-}

option selected	number selecting
C is more stable than A	0
C and A are equally stable	8
C is less stable than A	8
I do not know which statement is correct	0
total	16

Table A3.6: relative stability of Na^{7-} and Na^{+}

The results of this class exercise were that most of the students in the small sample thought that the Na^{+} ion was more stable that the Na atom (81%), and also that the Na^{7-} ion was more stable than the Na atom (63%). Half the students thought that the sodium anion was less stable than the sodium cation, but the other half thought they were equally stable.

This result suggest that the unexpectedly high support for item 18 in the TRUTH ABOUT IONISATION ENERGY DIAGNOSTIC INSTRUMENT was probably *not* due to misunderstanding the intended meaning of the statement. It would seem that many A level chemistry students who have studied topics such as bonding and ionisation energy do believe that the sodium "***atom would become stable if it either lost one electron or gained seven electrons***".

The fourth part of the Chemical Stability question asked the students to "explain the reasons for [their] answers to questions 1-3". The points made have been summarised in table A3.7.

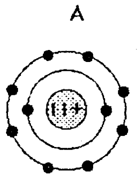
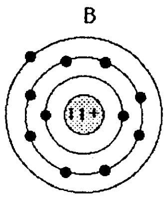
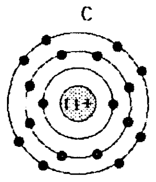
diagram	points made about species
A (Na^+ ion)  figure A the sodium one plus ion	• stable electron(ic) configuration • complete octet • complete [full] outer shell - therefore stable • noble gas configuration • does not need to react as electron shells full • stable as shell contains the full requirements • full outer shell with +1 charge, so likely to react • valency requirements fulfilled • lost the one electron in valence shell therefore more stable • in bonding state as +1 ion - so more stable • electrons are closer to the nucleus • lower energy configuration because smaller • higher charge:radius value therefore more stable • positive ion more reactive • will react with one negative ion • stable as most used ion
B (Na atom)  figure B· the sodium atom	• one electron on outer shell - very unstable • one free electron so less stable • one electron on its own, so likely to react • more likely to donate • needs to lose an electron • looking to satisfy its outer shell • not have full outer shell • natural form - so stable • needs another 7 electrons to fill the outer shell, will react more easily to gain electron, so not as stable • only one electron free, so less likely to react
C (Na^{7-} ion)  figure C: the sodium seven minus ion	• stable electronic configuration • noble gas configuration • full outer shell therefore stable • valency requirements met / fulfilled so stable • 7- ion strongly attracts many positive ions • react with seven [positive ions] / more than one +1 ion • cation is normally formed / more likely • not the common ion - so less stable • not usually get 7 electrons • -7 charge large, so less stable • high number of electrons - easily under electrophilic attack • greater shielding • more electrons repelling against electron to be removed • not full outer shell, i.e. 18 • needs to lose 8 electrons to become stable

Table A3.7: student reasoning on chemical stability question

It can be seen from this table that many of the students based their decisions on the FULL SHELLS EXPLANATORY PRINCIPLE, referring to stable and noble gas electronic configurations, full shells, octets and fulfilled valency requirements. These responses demonstrated a wide range of subtle variation, but clearly relate to the features of the OCTET RULE FRAMEWORK developed and presented in chapters 11 and 12. The following answer is clearly focussed on full shells, but was unusual in that the anion was *not* seen as an example of a species with a full shell,

> "A is more stable than B because it contains a full outer shell i.e, it has eight electrons in its outer shell. Its configuration is therefore similar to that of a noble gas. B is not as stable as A because it does not have a full outer shell of electrons i.e, eight electrons. It needs [sic] to lose an electron to become stable ... C is less stable than A because C does not contain a full outer shell of electrons. ie. 18 whereas A does, i.e. 8"

The following answers did consider both ions to have full outer shells,

> "1. A is more stable than B because its outer shell electron has eight electrons and is full where as B only has one electron in it's outer shell and is therefore less stable.
> 2. B is less stable than C because again the outer shell of C is full with eight electrons but B only has 1 electron in its outer shell and is less stable.
> 3. C and A are equally stable because both outer shells are full and the valency requirements have been fulfilled. Therefore both are equally stable."

> "1) I have said that A is more stable than B because it has a full outershell
> 2) B is less stable than C because B has one free electron and C has a full subshell
> (3) I have said that A and C are equally stable as they both have full outer shells."

> "With A all the electron shells are full so they don't need to react to gain another electron.
> B is not as stable as C because it needs [sic] another 7 electrons to fill the outer shell and will react more easily to gain electrons.
> C and A are equally stable as they both have full outer shells."

> "1 - A is more stable than B because it has a full outer-shell of electrons whereas B has only one electron in its outer shell and it is very likely that it will lose that electron.
> 2 - B is less stable than C again this is because C has a full outer shell of electrons whereas B has only one electron in the outer shell.
> 3 - A and C are equally stable because both A and C have full outer shells."

> "An element is 'more' stable if it electron requirements are satisfied, ie: A sodium atom with a one plus ion would be more stable than the usual sodium atom as all its shells contain the full requirements. Figure C is also stable even though it contains 7 minus ions as the valency requirements are satisfied."

> "1. A has a complete outer shell, whereas B has one electron in it's outer shell making it very unstable. If B loses that one electron it becomes the stable A.
> 2. C also has a full outer shell making it stable, whereas B is unstable with it's one outer electrons.
> 3. Both A and C have full outer shells and are therefore both stable. Although C has an extra shell, it still remains as stable as A."

The following answer used the 'core charge' concept, which is a tool from the electrostatic framework, but only to erroneously offer support for the octet rule view by suggesting that both the cation (core charge +9) and anion (core charge +1) had the same core charge.

> "A) 'A' is more stable than 'B' because it has a stable electron config. and the electrons are closer to the nucleus.
> B) 'B' is less stable than C, because B has one electron on its outer orbital, making it very unstable, the atom will more likely to "donate" its outer electron to other atom.
> C) A and B are equally stable as they both have stable electron config. and the same core charge."

Finally, the following answer is of particular interest as it demonstrates that the octet rule definition of stability may be applied, even when the student is fully aware of more conventional energetics. The answer acknowledges that ionising a sodium atom requires (or "wastes") energy, but from within the OCTET RULE FRAMEWORK this does not negate the stability of the product,

> "Sodium has to fulfil its valency requirements. It has 1 valence shell electron, to become stable, it can either lose one electron or gain seven, losing one electron would be less energy wasted but either way both are stable. A is more stable than B as it has a full outer shell unlike the atom. and C is more stable than B as it also has a full outer shell
> C & A are equally stable - the 7- ion has one more shell & is bigger but are both equally noble and unreactive."

There was some reasoning calling upon students' electrostatic frameworks, such as the seven-minus ion strongly attracting positive ions, being open to electrophilic attack, and having more electrons repelling, but there were only a few comments based in electrostatics in the comparison between the sodium atom and the cation. The following response has valid conclusions, although it contains anthropomorphic language,

> "1) I ticked A is less stable than B because A becomes an +ve ion which will be more reactive than an atom due to it's positive ness[?] being attracted to negative ions. Whereas although B is looking to satisfy [sic] it's outer shell it's still less reactive than A.
> 2) B is more stable than C because C is a -7 ion which strongly attract many positive ions to become a neutral molecule [sic].
> 3) C is less stable than A a [sic] because C is -7 ion + A is a +1 ion. As c is -7 it's going to react more with positive ions and Although A will also react it's got to react with one negative ion to satisfy itself [sic] whereas C will have to react with 7."

The following response seems to use an OCTET RULE FRAMEWORK as a primary criterion to decide that the atom is least stable, but then applies electrostatic considerations to decide between the two ions,

> "I believe that A is the most stable as it has lost one electron in its valence shell and therefore will be more stable than B, as B still has this one electron in its valence shell and this makes it very unstable. A has a noble gas configuration as does diagram C but the attraction between the 11+ core [sic] charge and the 10 electrons on diagram A are stronger than the 11+ core charge and the 18 electrons in diagram C. The shielding in C will also be greater as there are more electrons repelling against and electron that could be removed from C in comparison to A."

The following response introduces size as an important factor, and refers to the ratio charge:radius. However, this concept is used in a manner contrary to CURRICULUM SCIENCE (i.e. a higher charge:size value would lead to greater reactivity),

> "A is more stable than B because here it is in its bondingstate as as the one plus ion. Its bondingstate is at a lower energy configuration than B because now the ion is smaller. B is more stable than C as C has -7 charge the atom is very large \ with such a high number of electrons these will easily be under electrophilic attack. The same reason for A. It should be more stable because it has a large charge:radius value \ more stable."

There were also some comments about what was natural or normal: the atom was the natural form of sodium, and the cation was the most used [sic] ion, whilst the anion was not common. It was not clear from the brief comments whether these were references to a belief in *natural states* (c.f. the explanatory gestalt of essence, see chapter 2, §2.4.4), or simply a sensible use of the principle that was is familiar is more likely to be stable (as after all what is more stable is more likely to be familiar!)

> "1 - a + b are equally stable because B is the natural form, and a is the most used ion of sodium.
> 2 - c is not the common ion so I assume it would be less stable than the natural atom itself
> 3 - C is not the common ion so therefor I again assume it is not as stable as the common ion which is more regularly formed."

In the following answer the primary criterion for comparing the two familiar species again appears to be the OCTET RULE EXPLANATORY PRINCIPLE, but the anion's unfamiliarity, or abnormality, is used as a criterion to suggests its lack of stability

> "1. A is more stable than B as it has a complete octet, while B has one extra electron.
> 2. B is more stable than C because B will normally form a cation, not a 7- anion.
> 3. C is less stable than A because a 1+ve cation is more likely. The sodium atom will not get 7 electrons usually."

The instrument was also presented to a group of new A level students as part of a series of induction exercises. The results from this group of 13 students are given in tables A3.8-11.

option selected	number selecting
A is more stable than B	11
A and B are equally stable	0
A is less stable than B	2
I do not know which statement is correct	0
total	13

Table A3.8: relative stability of Na^+ and $Na^\bullet$

option selected	number selecting
B is more stable than C	2
B and C are equally stable	0
B is less stable than C	11
I do not know which statement is correct	0
total	13

Table A3.9: relative stability of $Na^\bullet$ and Na^{7-}

option selected	number selecting
C is more stable than A	1
C and A are equally stable	9
C is less stable than A	3
I do not know which statement is correct	0
total	13

Table A3.10: relative stability of Na^{7-} and Na^+

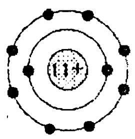
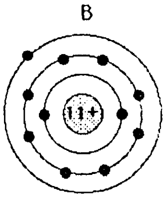
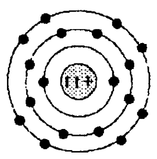
diagram	points made about species
A (Na^+ ion) A  figure A the sodium one plus ion	• A has a complete/full outer shell (5) • A has 8 electrons in outer shell (5) • A has the maximum number of electrons • A does not want any more electrons • A does not need to gain any more electrons • A has the right amount of electrons • A has a greater valency • A is positively charged
B (Na atom) B  figure B the sodium atom	• B is looking to loose a electron • B would find it easy to lose an electron • B needs to lose an electron (2) • B is neutral • B is neutrally charged • B wants to lose an electron • B has a tendency to lose an electron • B needs to react with something because only one electron in outer shell
C (Na^{7-} ion) C  figure C: the sodium seven minus ion	• C has a greater valency • C is negatively charged • C has a complete/full outer shell (4) • C's outer shell has 8 electrons (4) • C has the right amount of electrons • C has more electrons in its atom, and 8 electrons on its outer shell • C would find it more easy to lose electrons [than A] because the outer shell is further from the nucleus • C has a greater valency [than A] • C has a bigger difference between the numbers of protons and electrons

Table A3.11: student reasoning on chemical stability question (induction exercise)

This group gave a similar pattern of responses, in that again the ions were seen as more stable than atomic sodium. Overall there was even more support for seeing Na^{7-} as a stable species in this group just embarking on A level chemistry, with eleven of thirteen respondents (85%) considering Na^{7-} more stable than $Na^{\bullet}$, and ten of thirteen respondents (77%) considering Na^{7-} at least as stable as Na^{+}.

Finally, one of the responses might stand as an definitive statement of the alternative notion of chemical stability based on the OCTET RULE EXPLANATORY PRINCIPLE:

> "If an atom has been filled up or all ready full up of (8 outer electrons) it becomes stable and therefore it is unreactive. The atom will stay that w forever and not react or loose or gain any electrons."
> (A level student, written induction exercise, September 1995).

Appendix 4.

The chemistry student's toolbox.

§A4.1: The G.C.S.E. chemistry student's toolkit.

§A4.1.1: Chemical Bonding - what does the G.C.S.E. chemist have in his or her toolkit?

A student who has successfully completed a G.C.S.E. course (more likely 'double science' than chemistry at the present time) and intends to move onto an A level course in chemistry would be expected to already have a certain level of knowledge and understanding of chemical ideas. For example the student should have acquired versions of the following concepts that are generally compatible with the CURRICULUM SCIENCE versions: **atom**, **molecule**, **element**, **compound**, **ion.** The student should have some knowledge of sub-atomic particles (**protons**, **neutrons**, **electrons**) and the rules that relate them to **atomic number** and **atomic mass**.

A model of **atomic structure** at the Rutherford-Bohr level is expected: i.e. the central **nucleus** surrounded by '**shells**' of electrons, an arrangement described by the **electronic configuration** (E.C., e.g. E.C.(Na) = 2.8.1). Students should know that protons have **positive** electrical charge and electrons (an equal magnitude of) **negative** electrical charge, and that atoms, and all stable substances (under the conditions of temperature etc., normally considered), are electrically **neutral** overall. Students should know the general rule that opposite charges **attract** and similar charges **repel** (this 'explains' why electrons do not 'fall out' of atoms, but does not explain how all the positive charge is concentrated at the central point of the atom).

An additional tool for understanding chemical bonding is the so called '**octet rule**'. This is the idea that most electronic configurations are unstable compared to those of the noble gases, which are sometimes said to have 'full shells': i.e. He = 2, Ne = 2.8 and Ar = 2.8.8 (the outer shell of argon is not actually full: only the 3s and 3p 'sub-shells'). In stable materials (that is, those studied to this level) atoms may be considered to have noble gas electronic configurations (**N.G.E.C.**). The noble gases are (were!) called *inert* as they do not react (there is a limited chemistry for the heavier noble gases, but this is not considered at G.C.S.E.).

In chemical terms the category **metal** is used to describe an element which has a small excess of electrons over a N.G.E.C., and a **non-metal** has a small deficit compared to the next N.G.E.C. (Students will already have a concept of 'metal' which is likely to be closer to an engineering meaning of the term: although cæsium is hardly a useful metal for making bridges, and copper is chemically a weak metal, the two categories essentially include the same elements. When students study the reactivity series of metals they become aware that some 'metals' have a greater tendency than others to form cations. However there is still a tendency that the useful categories metal and non-metal are seen largely as a dichotomy, with a few anomalous semi-metals as exceptions.)

There are then two ways to produce compounds which are neutral overall, and contain atoms which have N.G.E.C. If two atoms **overlap** their outer shells so that a pair of electrons - one originating in each shell - are now in both shells each atom may be considered to have one extra electron in its configuration. A **shared** pair of electrons constitutes a **covalent bond** between the atoms.

Metal atoms tend to 'lose' electrons to form **cations**. Non-metal atoms tend to 'gain' electrons to form **anions**. (Stable ions usually have N.G.E.C.) Cations and anions will attract each other and be held together by **ionic bonds**, a.k.a. **electrovalent bonds**.

The concept of **valency** (or bonding ability) is related to electronic configuration, and therefore the **periodic table**. An element's **covalency** is the number of covalent bonds it would form to achieve a N.G.E.C., and its **electrovalency** is the number of electrons that needs to be lost or gained to achieve the nearest N.G.E.C. (and would be positive or negative respectively). E.g. N [e.c.= 2.5] has covalency of 3, and electrovalency of -3. Magnesium [e.c. = 2.8.2] has an electrovalency of +2 (it cannot have a covalency in the normal sense as it would need to form six covalent bonds to reach the next N.G.E.C., but only has 2 electrons to share.)

These G.C.S.E. level ideas, with emphasis on N.G.E.C. and two types of bond, represent the chemical bonding theory published in 1916 by Lewis and colleagues (Pickering, 1977). The general approach can be described as the **valence bond model**, and the simple diagrams (using lines as covalent bonds or dots and crosses as electrons can be called **Lewis structures**.

It will be noted that even in this very brief survey of what would be expected knowledge of bonding as prerequisites for studying chemistry at A level, there are a considerable number of concepts (shown in bold type): all abstract (as all relate to hypothetical entities such as atoms, about which no direct concrete experience is available to the average sixteen year old student), and inter-related through a complex web of connections.

§A4.1.2: Some comments on the G.C.S.E. bonding toolkit.

1. At this level molecules may be represented with simple two-dimensional diagrams, such as Lewis structures, which show the essential features (i.e. valence shell electron occupancy, number of bonds [= pair of shared electrons], number of atoms of each element present in molecule and structural arrangement - which is bonded to which). It is also simple to show electron transfer, and ions formed, and two-dimensional representations of ionic lattices. The valence bond approach is still used for many purposes in texts intended well beyond G.C.S.E., and indeed in research papers. In organic chemistry most structures are drawn in terms of a representation that uses simple lines to stand for covalent bonds, i.e. pairs of shared electrons between atoms.

2. The level of sophistication outlined above is sufficient to explain many of the chemical phenomena studied during an A level course: the categories of metal and non-metal, ionic and covalent; and concepts such as valency continue to be useful and used - even thought they are no longer sufficient to explain all the phenomena to be considered.

3. For the sake of simplicity ionic bond formation is often represented by showing the minimum number of atoms for ion formation, for example Na + Cl changing to Na^+Cl^-. In practice if some salts are evaporated ion pairs will be formed *in the vapour*.

However, the large exothermic term involved in the formation of ionic compounds is lattice formation: although given sufficient activation energy two molecules of hydrogen would react with one molecule of oxygen to form two molecules of water, it may *not* be true that a single atom of magnesium would interact with a molecule of chlorine and form ionic magnesium chloride! In an ionic lattice the bond is due to the electrostatic attraction (at equilibrium the ions are subject to balanced attractions and repulsions - but if one attempted to disrupt the lattice by removing an ion one would be opposed by attractive forces) between each ion, and the counter ions close to it. Cations have no memory of which anion contains their donated electron(s), and anions likewise do not 'know' the donor of their accepted additional electrons.

4. Students starting an A level chemistry course will usually be aware of the existence of metallic bonding, but generally seem to have little detailed

knowledge: perhaps knowing of the 'sea of electrons', but not much more. This is understandable as metallic bonding cannot be so easily explained with a toolkit comprising of the tools outlined above.

5. The toolkit is also insufficient to explain a number of phenomena that do need to be discussed at A level (but not at G.C.S.E.):-

bond polarity
hydrogen bonding
electron deficient compounds (e.g. $BeCl_2$)
van der Waals forces
properties of benzene (and other resonant structures)
Fajan's rules
ionisation enthalpies, I.E., (patterns of S.M.F.I.E.s {standard molar first ionisation enthalpies} - how they vary across periods and down groups; also how successive ionisation enthalpies relate to e.c.), and successive I.E.s)
dative bonding and complexes

6. Concepts of stability are relative. An atom with a non-N.G.E.C. is only unstable in certain chemical environments: in an universe containing only one sodium atom it would be stable compared to the Na^+ cation and an electron donated to the void, whereas in a lump of sodium (or at the surface of a piece of sodium in a gas jar of chlorine) the atomic E.C. is unstable.

7. At G.C.S.E. level there is no attempt to explain the rationale behind the octet rule - it is accepted on the teacher's authority, or as empirically determined.

§A4.2: Additional tools that may be added to the toolbox during A level studies.

There is not a single rational order for introducing new concepts in this area of study. To some extent a degree of 'bootstrapping' is undertaken: the acquisition of one new concept will often be useful for the introduction of another, which in term helps develop a more sophisticated appreciation of the first. This area of knowledge is perhaps better understood as a network of related ideas, than a hierarchy of principles - certainly at the level of study being discussed. In the presentation that follows a generous use of **bold type** highlights some of these interconnections.

§A4.2.1: Electronegativity.

This concept may be defined as the tendency of an atom in a molecule to attract the bonding electrons towards itself. The definition could be learnt and applied without any appreciation of why some elements should be more electronegative than others. The trends of electronegativity in the **period table** may be learnt by rote, and related to the terms **metal**, **semi-metal** (metalloid) and **non-metal**. The existence of tables of electronegativity values allows students to appreciate that metallic - non-metallic properties form a continuum (but the terms metal and non-metal continue to be useful). This concept allows students to develop a concept of **polarity** in bonds. The pattern of **electronegativity** values in the periodic table may be explained in terms of **Coulomb**ic attraction.

§A4.2.2: Polar bonds.

Using the G.C.S.E. toolkit the bond between two hydrogen atoms may be understood as a pair of electrons *equally* shared between the two atoms. However in a 'covalent' bond between two different elements, with different electronegativities, the sharing will not be equal. A bond with unequal sharing of the bonding electrons is called a **polar** bond.

This type of bond may be understood purely in relation to the definition of electronegativity, or by considering the electrostatic attraction on the bonding electrons from each of the atomic **cores**.

The polar bond may be visualised in the simple Lewis type (i.e. G.C.S.E.) diagrams by showing the electron pair displaced towards the more electronegative atom. Another approach is to draw **electron density** diagrams and show the electron cloud distorted towards the more electronegative atom.

§A4.2.3: Coulomb's law.

Many processes of interest to chemists may be understood by considering electrostatic forces between point charges: the force is proportional to the product of the charges, and inversely proportional to the square of the separation. (The constant of proportionality and actual units are not significant here - unlike in A level physics - as we are using the relationship is a qualitative way to make comparisons.) Electrons may be considered as point charges for these purposes, as may nuclei and indeed (usually) **atomic cores**. We may use this law to explain **electronegativity**, **ionisation energies**, **Fajan's rules**, extent of **hydration** of ions and so forth.

In addition the basic idea that electrostatic attraction depends only on charge and separation (assuming no medium when working at this scale) explains why a pair of electrons bonds two hydrogen atoms together, why ions are held together in an ionic lattice, and metal ions in a metallic lattice. It will also explain the attraction between neutral but **polar** molecules, and even between **transient dipoles**.

§A4.2.4: Quantum theory.

The atomic hypothesis is itself a quantum theory of matter. That energy should also be quantised should perhaps be no more surprising than finding matter is not continuous. Students are not aware of the origins of quantum theory: when they start an A level chemistry course they would not be likely to know about the spectra of black body radiation, the photoelectric effect, nor the inherent instability of atoms according to classical mechanics.

Quantum theory explains the **periodic table** and **atomic structure** - but in terms of a set of abstract rules that seem arbitraryand 'given' at this level. Perhaps the most important consequence is the concept of the **atomic orbital**, which to some extent replaces the electron "shell" in work at this level.

Important components of the quantum theory of atoms for A level students include the **Pauli exclusion principle** (as electrons are fermions), the **Aufbau** principle (as at room temperature the difference in electronic energy levels is large compared with the thermal energy available, and it is usual to consider ground state atoms when determining electronic structures), and the idea of **Hund's rule** and electron **spin**.

§A4.2.5: Orbitals.

Atomic orbitals (which may be defined as *"the wavefunction of an electron moving under the influence of the nuclear potential and average repulsive potential of the other electrons"* {Murrell, Kettle & Tedder, 1978, p.64}) have quantum numbers which are related to orbital size (as they are infinitely large the measure of size relates to an electrons' most likely distance from the nucleus, which is *comparable* to shell in the Bohr atom), orbital geometry and orbital orientation. The **energy level** of the orbital (usually) depends on the first two factors, and in some (i.e. non-uniform electrical) environments on the third. (In a hydrogen-like system all orbitals with the same principle quantum number are degenerate. In multi-electron systems the wavefunction (orbital) of one electron is effected by the repulsion of the other electrons and this degeneracy is razed. In these (i.e. most) cases the energy for a given value of n is $s < p < d < f$). As atomic orbitals have infinite extent, and chemists usually value visual representations, an envelope is usually drawn representing the volume of space where an electron has a high probability of being detected. (If a student interprets this envelope as a limiting boundary there are few practical consequences at this level.) **Electron density** diagrams may either represent a single probability envelope, or a contour map of the varying electron density. Diagrams of this sort enable **polarisation** of bonds to be shown clearly.

The types of **atomic orbitals** of interest at this level are **s, p** and **d orbitals**, and **hybrid** orbitals. (Diagrams representing atomic orbitals are usually based on the results from an isolated hydrogen atom. Atomic orbitals for multi-electron atoms can in principle be obtained - by self-consistent field methods - but are much more difficult to calculate. Approximate methods are available, such as that due to Slater. The Slater orbitals obtained from the calculations are similar in general form to those obtained for hydrogen {e.g. McSweeny, 1979, pp.27-45}.)

The concept of **electronic configuration**, used at G.C.S.E. level, becomes more sophisticated once students are aware of atomic orbitals, for example the electronic configuration of ground state carbon, 2.4, is in more detail $1s^2$ $2s^2$ $2px^1$ $2py^1$.

An interesting tool is the simple diagram:

1s					
2s	2p				
3s	3p	3d			
4s	4p	4d	4f		
5s	5p	5d	5f	5g	etc.

which when traced through by a series of diagonals (from top right to bottom left) gives the order of filling orbitals: 1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s and so on.

§A4.2.6: Polarisation of ions.

An isolated anion with a **N.G.E.C.** has a spherical distribution of **electron density** (which may be readily represented in two dimensions as a circle). If a cation is brought near the anion there will be a **Coulombic** interaction between the ions, and they will attract. However ions are not rigid and the valence shell electrons in the anion will be pulled toward the cation, as well as towards the anionic **core**. The result will be some distortion of the **electron density** of the anion towards the cation. (There will also be some influence on the cationic electron density due to the repulsion of the anionic charge - but this will tend to be less, as prescribed by Fajan's rules). This may be construed as the introduction of some **covalent** (electron sharing) **character** in the bond, and if significant could lead to a bond that is better described as **polar** than **ionic**. For example the bonding in HF could be modelled by considering the formation of ions, H^+ and F^- by electron transfer, followed by distortion of the fluoride ion to give a polar bond. This is an alternative to modelling HF as a covalent bond which is polarised by the greater electronegativity of fluorine.

As with the case of 'covalent polar' bonds it would be possible to represent the polarisation in terms of **Lewis diagrams**, although it is perhaps clearer showing various degrees of **polarisation** using **electron density** diagrams.

It is intended that students working on the ideas of **polarisation** of both covalent bonds and ionic bonds will come to see that these two categories represent the extreme ends of a continuum of **bonding character**. (It would be possible to consider extreme cases. For example to think of potassium chloride as covalent, and consider the extent of polarisation (extreme); or an ionic lattice made up of hydrogen hydride (H^+H^-) where the cation distorts the electron cloud around the anion to such a great extend that it becomes a pure covalent bond.)

§A4.2.7: Character of bonding.

Most bonds in real compounds fall somewhere between pure covalent (equal electron sharing) and pure ionic (total electron transfer) bonds. Chemical data books provide tables suggesting how the difference in **electronegativity** between two atoms is related to the percentage ionic character in the bond (e.g. Stark and Wallace, 1982, p.25). Thus most bonds are **polar** to some extent: this may be visualised by **polarisation** of covalent or ionic bonds, or alternatively as the structure being a **resonance** of covalent and ionic **canonical forms**.

§A4.2.8: Core charge.

A full shell of electrons has overall spherical distribution of electron density. From a point outside a sphere of electrical charge the charge may be considered to be acting as a point charge located at the centre of charge (which will be at the nucleus). Consequently for an ion the electric field is that of a charge of magnitude = nuclear charge - total electronic charge, located at the nucleus.
(E.g. for Na^+: 11 - 10 = +1; for S^{2-}: 16 - 18 = -2.)

For an atom the electric field experienced by a valence (outer shell) electron may be considered to be that due to the core charge

core charge = nuclear charge - shielding (inner shell) electrical charge

e.g. for Mg (2.8.2) : core charge = 12 - (8 + 2) = +2
for Cl (2.8.7) : core charge = 17 - (8 + 2) = +7
for Br (2.8.18.7): core charge = 35 - (2 + 8 + 18) = +7

(note that the core charge is related to periodic table group.)

Thus core charge is a tool for approximating the effect of the nucleus and all the inner shell electrons in one entity. (This approach is rather simplistic. Slater has produced weightings for shielding including same shell electrons and taking quantum number l into account: for example one 1s electron shields another to an extent of 0.30, and a 3d electron shields a 4p electron to the effect of cancelling 0.85 of a proton charge.) The concept of core charge is useful (in conjunction with **Coulomb's law**) with understanding the patterns in **ionisation enthalpies**. The concept may also be used to help understand bond polarity in covalent bonds as the bonding pair may be considered as valence shell electrons of both atoms.

(For example consider a C-Cl bond in CCl_4. Carbon has a core charge of +4 and a covalent radius of 77 pm, and chlorine has a core charge of +7 and a covalent radius of 99 pm. A bonding electron placed 77 pm from the carbon nucleus and 99 pm from the chlorine nucleus will experience a Coulombic force of 675 (arbitraryunits) pulling it towards the carbon nucleus, but 714 (same units) towards the chlorine nucleus, so there would be a net force displacing the electron towards the chlorine. This analysis ignores the repulsion from the other valence shell electrons.)

§A4.2.9: Orbital Hybridisation.

The s, p, d and f atomic orbitals, occupied as given by **Aufbau**, represent the **ground state** for an atom. These atomic orbitals may be **rehybridized** (with an appropriate energy input) to give hybrids with more appropriate geometry for the orbital overlap needed for bond formation. A number of simple rules may used to outline this process:

(i) the number of hybrids produced is equal to the number of ground state orbitals hybridized (e.g. s + three p gives four sp^3.)

(ii) the *overall* geometry of the interacting orbitals does not change (so that four sp^3 hybrids are spherically symmetrical overall, as are s + three p orbitals taken together; sp^2 orbitals are formed in the plane defined by the two p orbitals hybridized, and are therefore orthogonal to the unhybridized p orbital).

(iii) the energy of hybrids will be between that of the contributing orbitals (e.g. an sp hybrid is at a higher energy level than the s orbital, but at a lower energy level than the p orbitals).

(iv) the number of electrons to occupy the orbitals does not change, and the usual rules apply (**Pauli**, **Hund**).

§A4.2.10: Ground and excited states.

The **Aufbau** principle describes the lowest possible electronic energy state, or ground state, for an atom. (Atoms also have translational energy, and molecules also have rotational and vibrational energy - these quantities are also quantised, but the quantum jumps are much smaller. At room temperature most molecules will not be in rotational ground states.) A suitable photon may provide the appropriate energy quantum to produce an electrical quantum jump to an excited state (usually indicated by an asterisk), e.g. E.C.(H*) = $1s^0\ 2s^1$.

Rehybridisation leads to an excited state (for example consider a ground state oxygen atom ($1s^2\ 2s^2\ 2p^4$) rehybridising to form four $2sp^3$ hybrids ($1s^2\ (2sp^3)^6$): as two of the hybrids are only singly occupied the full s-character available is not being used: the six electrons occupy orbitals of 1/4 s character, and 3/4 p character, c.f. 1/3 s and 2/3 p character in the ground state. (Rehybridisation to give three $2sp^2$ hybrids should not produce an overall energy level change - but this arrangement would not lead to bond formation unless an electron was subsequently promoted from one of the hybrids to the (higher energy) unhybridized p orbital.)

§A4.2.11: Molecular orbitals.

When two atoms are brought close together their atomic orbitals can overlap. The interaction of atomic orbitals can lead to the formation of molecular orbitals. When the two atomic orbitals are of similar energy and are able to overlap significantly they will give rise to two molecular orbitals, one at a higher energy than the contributing atomic orbitals, one lower. (As atomic orbitals extend to infinity the atoms do not need to be *that* close for some interaction to occur! However, unless the overlap is significant the atomic orbitals may to a good approximation be consider unperturbed.) If each of the interacting atomic orbitals is singly occupied the electrons may form a bonding pair in the lower energy, or **bonding, molecular orbital**. (In dative bonding both electrons begin in one atomic orbital.) The higher energy orbital produced is called the **antibonding molecular orbital**, which is unoccupied. (It is possible to consider the outcomes if the two interacting atomic orbitals are occupied differently. If both are occupied by two electrons before interaction there will be no bond formed. If the two orbitals contain one or three electrons between them it would be possible to form a bond of order 0.5. These possibilities are not normally discussed in detail at A level.) It is possible for more than two atomic orbitals to interact, in which case the number of molecular orbitals produced equals the number of atomic orbitals contributing. (For example, if three orbitals of equal energy interact the third orbital produced (of the same energy as the atomic orbitals) is non-bonding. In benzene six p orbitals overlap to form six molecular orbitals: three bonding (one of lower energy level than the other two) and three antibonding. Each molecular orbital can only be occupied by two electrons (as each electron in the system must have a unique set of quantum numbers) so all three bonding orbitals are used. At A level it is often only the lowest energy bonding orbital - produced by combining all six atomic orbitals with the same phase on each side of the planar structure - that is depicted).

In organic chemistry there has been considerable effort to study molecular orbitals, as the so-called **frontier** molecular orbitals - the highest occupied molecular orbital, HOMO, on one molecule, and the lowest unoccupied molecular orbital, LUMO, on a second molecule - are considered to be especially important in many reactions between molecules.

Significant overlap not only implies the atoms being close but requires that the symmetry properties of the orbitals are matched (an s-orbital in side-on overlap with a p-orbital will not produce a bonding orbital as the p-orbital has a different phase on either side of the nucleus) and the geometry of the orbitals being suitable to give good overlap. In effect this usually means that strong bonds are formed from orbitals which have most of their electron density in a lobe pointing away from the nucleus: two such lobes may give good overlap along their mutual axis. It is for this reason that **hybrid atomic orbitals** are often involved in bonding. (As poor overlap does not significantly perturb atomic orbitals we may *to a first approximation* assume that lone pairs and core electrons are not affected by bond formation.)

The symmetry of the bond (bonding molecular orbital), and its geometry derives from the combining atomic orbitals:

sigma (σ) bonds (i.e. bonding molecular orbitals) have a single concentration of electron density which is symmetrical with respect to rotation about the bond axis, and are formed by the overlap of two orbitals along the axis.

pi (π) bonds have two areas of electron density, symmetrical with respect to reflection in a plane passing through the bond axis, and are formed by (sideways) overlap of atomic orbitals with two lobes. (At A level this means 'sideways' overlap of two p-orbitals, but pi-bonds could also be formed for example by overlap of a p-orbital on one atom with two lobes of a d-orbital on another atom. Delta (δ) bonds may be formed by 'sideways' overlap of two d-orbitals, but this is not usually studied at A level.) The mirror plane will be that described by the atomic p-orbitals orthogonal to those being used to form the molecular orbital.)

The production of molecular orbitals from atomic orbitals may be understood as being the result of a simple arithmetic process (adding the electron density for same phase lobes leading to bonding orbitals, subtraction giving the anti-bonding orbitals). This tool is given the title **Linear Combination of Atomic Orbitals (L.C.A.O.)** (It should be realised that L.C.A.O. is only an approximation method - but one that is based upon assumptions that are considered reasonable to physical intuition, and which gives answers that do approximate to the empirical data. It should also be realised that it is not the electron density itself which is subject to the arithmetic, but the wavefunctions, ψ, which can take negative as well as positive values, whereas the electron density is identified with (the always positive) $\psi * \psi$. {i.e. "An atomic orbital is a function y(r) of the coordinates of the electron, and, in accord with the Born interpretation of the wavefunction, the probability that the electron may be found in an infinitesimal volume element, $d\tau$, surrounding the point r is $\psi^*(r)\ \psi(r)\ d\tau$" (Atkins, 1974, p.9)}. For A level students a discussion in terms of the more visualisable electron density is usually considered an appropriate - if not rigorous - approach.)

§A4.2.12: Metallic bonding.

It has already been noted that metallic bonding does not seem to be studied in detail in most G.C.S.E. courses. A regular arrangement of closely packed cations surrounded by the 'sea' of delocalised electrons acting like a 'glue' to the structure, might be the most sophisticated approach taken. The **L.C.A.O.** model allows a more sophisticated approach, seeing the entire crystal as a giant molecule, with outer **atomic orbitals** combined to produce an equal number of closely spaced **molecular orbitals** for the valence electrons to occupy: as metals have less than half occupancy of their valence atomic orbitals the resultant structure has only **bonding molecular orbitals** filled. The large number of orbitals spread through a modest energy gap means than the energy levels form a virtual continuum allowing electrons ready movement into (vacancies in) adjacent orbitals - and thus forming an explanation for conduction. (The energy gaps are much smaller than those between atomic energy levels, and at normal temperatures these gaps are much smaller than the thermal energy distributed among the electrons.)

Solid insulators, such as ionic crystals, may also be explained in terms of such a **molecular orbital** model, with a full **valence band**, but an empty **conduction band**, and both intrinsic and extrinsic **semiconductors** may also be explained this way. Despite its explanatory power, and its close affinity to the ideas used in considering **molecular orbitals**, band theory in solids is not usually subject of much discussion in A level chemistry - even though the ideas may be used in A level physics, where atomic energy levels are discussed less!) (In my own College, at the time the data collection was undertaken, we taught the band theory of conductors and insulators in the first year of an A level *physics* course, but do not explicitly study *atomic* energy levels until the second year when quantum theory is considered.)

§A4.2.13: Hydrogen bonds.

The hydrogen bond tool is used to explain such otherwise anomalous phenomena as the high melting temperature of ice. It could be understood as an example of **dipole-dipole interaction**, i.e. the positive end of one molecule being attracted to the negative end of another molecule. Thus a simple **Coulombic** model may be used to explain why **polar** molecules 'stick together'.

An alternative approach would be to envisage that the **hydrogen bonded** complex is a **resonance** of several **canonical forms**: the major contribution being the normal molecular structures, but additional contributions being made by the canonical forms having the hydrogen bonded atoms shown as formally bonded.

However, hydrogen bonds are unusually 'strong' for intermolecular interactions, typically about 10% of the strength of a covalent bond. In addition hydrogen bonds take up particular orientations: in water the hydrogen bond has a linear relationship with the covalent intramolecular hydrogen-oxygen bond. This geometrical restriction indicates that simple electrostatic interaction is not a full explanation - there is an involvement of orbital overlap between the hydrogen bonded entities, with new (supra)**molecular orbitals** being formed .

§A4.2.14: Resonance.

The concept of resonance is a tool for understanding some substances with properties that can not be explained using **valence bond** method in the normal way - i.e. drawing a single structure with all atoms satisfying their standard valence requirements. For example the Kekulé structure for benzene suggests that this compound should readily undergo addition reactions and should have two distinct types of C-C bonding - three bonds each with **bond orders** 1 and 2 respectively. Benzene doe not exhibit the chemistry predicted, and it has six similar C-C bonds (of order between 1 and 2). The true chemical behaviour is understood with reference to **molecular orbital** theory. The physical properties - bond lengths and angles - may be understood by considering the true molecular structure to be a 'resonance' (a kind of weighted average) of the feasible valence bond structures - the so-called **canonical forms**. (In the case of benzene the resonance is usually considered to comprise of five canonical forms: the two possible Kekulé structures contributing about 80% to the resonance, and the three Dewar arrangements the other 20%.)

Although it is often possible to envisage a number of feasible valence bond structures for a molecule, for example a version of methane comprising of four H^+ ions and a C^{4-} ion, it is considered that only structures of similar energy will make significant contributions: so an ionic structure for methane is unlikely to contribute significantly to the resonance, but an ionic contribution to a **polar** molecule such as HF would be important in understanding the compound.

A student with a good understanding of the **molecular orbital** approach probably gains little from the use of the resonance concept, but few A level students are fully at ease with **molecular orbitals**, and for the majority resonance is a useful tool.

§A4.2.15: Van der Waals' forces.

If there were no forces between molecules then ionic and macromolecular materials would be solids, but other compounds would be gases at all temperatures. There are three types of intermolecular bonding:-

dipole - **dipole** interactions: which are explained by assuming a **Coulombic** attraction between molecules with positive and negative 'ends'.

dipole - **induced-dipole** interactions: where the charged end of a **polar** molecule polarises the electron cloud in a non-polar molecule, and then the opposite charges attract (comprehendible as a **Coulomb**ic process)

induced-dipole - **induced-dipole** interactions: where **non-polar** neutral species attract, for example iodine molecules in an iodine crystal. The explanation for this involves envisaging the electron as a *mobile* point charge, moving about the **orbital** it occupies. As the electrons move the molecular **electron density** will shift and small **transient fluctuating dipoles** will occur. The **Coulombic** interaction between the fluctuating dipoles in adjacent molecules can result in the molecular dipoles fluctuating in phase so that the dipoles are in approximate alignment, and the molecules are attracted together.

Sometimes the term van der Waals' forces is used to describe all these types of interactions, but other texts restrict the use of the term to the latter case.

§A4.2.16: V.S.E.P.R.T.: Valence Shell Electron Pair Repulsion Theory.

This theory is a tool for explaining the shapes of simple covalent molecules. It considers that the arrangement of electrons in the valence shell of an atom may be understood by assuming the pairs repel each other through simple Coulomb type forces. The theory gives simple rules to establish the spatial arrangement of 1, 2, 3, 4 or more pairs of electrons. The molecular shape - to a first approximation - is determined by considering the spatial arrangements of the **bonding pairs**, e.g. in H_2O, oxygen has four valence pairs, in an approximate tetrahedral arrangement. The two O-H bonds are therefore arranged with an approximate tetrahedral bond angle (i.e. 109.5°), and the molecule is 'bent' or 'angular' in shape.

The reason this approach gives an *approximate* answer is because the four electron pairs are not equivalent. The electron pair in a bond experiences the attraction of both nuclei, and therefore their equilibrium position is further from the oxygen nucleus than that of the oxygen **'lone' pairs**. (From an **orbital** viewpoint the lone pairs are in $2sp^3$ **hybrids**, but the **bonding pairs** occupy **bonding molecular orbitals** obtained from the combination of oxygen $2sp^3$ **hybrids** with hydrogen 1s **orbital**.) If the four electron pairs were in a true tetrahedral arrangement the **lone pairs** would be closer to each other than to the **bonding pair** (and would repel each other more), and the **lone pairs** would be closer to the **bonding pairs** (and repel them more) than the **bonding pairs** are to one another. At equilibrium the bond angle is less than tetrahedral (104.5°) so that the four valence electron pairs are equidistant and repulsions are balanced.

There is a simple heuristic for remembering the result of this analysis:

l.p.-l.p. > l.p.-b.p. > b.p.-b.p.
(l.p.: lone pair of electron
b.p.: bonding electron pair)

where the property considered is the angles between electron pairs.

§A4.2.17: Electronic spin.

Each atomic orbital is described by three quantum numbers. Each electron in a system must have a unique set of quantum numbers (**Pauli** exclusion principle), but each orbital can be occupied by two electrons, provided that they have different values of the fourth quantum number - said to represent spin, and having only two possible values for electrons. If electrons are imagined as small particles they can be envisaged as spinning in the same manner as a cricket ball - however if electrons are considered as probability waves, or as point charges, it is not easy to see how electronic spin relates to the 'everyday' meaning of the term. (Atkins explains that "the spin is the intrinsic, characteristic, and irremovable angular momentum of a particle. A *convenient fiction* is to suppose that the spin is the angular momentum arising from the rotation of a body about its own axis: this model enables one to recall most of the properties of quantum mechanical spin, and in particular to understand (albeit at only a shallow level) why charged particles with spin also posses an intrinsic magnetic moment" {1974, p.223}.)

Although spin-pairing may be understood in quantum mechanical terms, this level of quantum theory is beyond an A level course, and some students appear to find difficulty in accepting that two electrons should occupy the same orbital. This is one area where the **Coulomb**'s law tool does not help us! (Atkins, again, explains that "electrons with parallel spins tend to stay apart, and those with opposite spins tend to bunch together. This remarkable phenomenon has nothing to do with the charge of the electron (although it affects the average Coulombic repulsion of two electrons and appears in the exchange energy) nor is it, one presumes, supernatural" {1974, p.224}.) My own non-quantum aid to understanding is to think of the spinning electrons as magnets arranged with opposite alignment so that the magnetic attraction opposes the electrostatic repulsion - a tool I do not rely on too heavily! (It would suggest that electrons in different orbitals should not be found spin-parallel where it is possible to arrange anti-parallel - in fact spin-parallel arrangements in degenerate orbitals lead to the ground state {i.e. **Hund**'s rule}).

§A4.2.18: Energy level diagrams.

Several types of energy level diagrams are used in chemistry at this level.

One simple type has energy as a vertical axis, and shows the difference in energy levels (usually qualitatively!) for reactants, products, transition states and intermediates where they exist. It is used to represent enthalpy of reaction (and to distinguish between endothermic and exothermic processes) and activation energy. The horizontal axis is sometimes referred to as the reaction coordinate (in more sophisticated versions it may represent specific inter-nuclear distances and can be replaced by a multi-dimensional surface).

The other type of diagram often used also has energy as a vertical axis, but unlike the first type is meant to show the energy levels of particular **orbitals** (atomic and/or molecular) and not the overall energy of a system of interacting molecules. The **energy levels** are usually shown as horizontal lines. Where there are several orbitals of the same energy (**degenerate**) they may be shown as distinct horizontal lines at the same vertical level. When used as a tool to understand bond formation the **orbital energy levels** of the reacting species are often shown at the sides of the diagram, and the resulting **molecular orbital energy levels** at the centre of the figure. For diagrams showing energy levels of atoms the horizontal axis may be used to separate **s, p, d** and **f orbitals** (e.g. McSweeny, 1979, p.36f.) Sometimes the **orbitals** themselves are represented as a series of boxes at the different **energy levels**. The electrons may also be shown, often symbolised by arrows representing them **spin-up** or **spin-down**.

A variation on this theme is also commonly used where the orbital 'boxes' are drawn on a horizontal line, with a vertical direction representing increasing energy - the convention is that boxes drawn touching are **degenerate**, and spaces represent an energy gap.

§A4.2.19: Electron pairs.

Using a purely electrostatic model of the atom electrons would be expected to move as far apart as possible. However **quantum theory** tells us that two electrons of opposite **spin quantum number** may occupy the same **orbital**. (The spin quantum number for an electron, m_s, can take values of $-{}^{1}/_{2}$ or $+{}^{1}/_{2}$! As the electron is often pictured as a small spinning top it is common for chemists to use the labels spin-down and spin-up to represent these possibilities.) For many purposes in A level chemistry it is a useful tool to be able to think of the electron pair as a discrete entity. (Atkins, once more, explains that "the tendency of spins to pair is a term too often ill-used in fallacious accounts of chemical bonding, where it is quoted as the *reason* why bonds form. Energy considerations govern bonding, and if by pairing electrons are enabled to enter a low-lying orbital, and so reduce the energy of the molecular system below that of the separated atoms, then pairing will occur. But rather than showing any transcendental mutual affection they are forced to pair (essentially by the **Pauli** exclusion principle) in order to achieve this low-energy state" {1974, pp.223-224, italics in original}). For example in explaining the shapes of molecules the **V.S.E.P.R.T.** considers the repulsion between *pairs* of electrons: either **bonding pairs** or **lone pairs** (a contradiction in terms unless an electron *pair* is seen as an entity).

Appendix 5.

Prerequisite knowledge.

Students undertaking A level chemistry are expected to have undertaken appropriate previous study (normally science at KS4, i.e. G.C.S.E. level). An analysis of the topic of *chemical bonding* led to the identification of a set of statements that could represent what would normally be assumed prerequisite knowledge relating to chemical bonding, at the outset of an A level course. This analysis is based on my own experience of teaching chemistry at G.C.S.E. and A level, and while it might not represent the precise expectations of other chemistry teachers, it informed my own thinking in setting out to undertake the research set out in this thesis. This appendix should be considered alongside the discussion of the chemist's toolbox in appendix 4.

(The statements are numbered G (for general level) 01 to 69, but this is purely for reference, and does not imply any hierarchy of importance or teaching order.)

G01 all substances are (matter is) made up of minute particles called atoms
G02 electrical charge exists in two types called positive and negative
G03 oppositely charged particles attract each other
G04 similarly charged particles repel each other
G05 atoms consist of a nucleus and one or more electrons
G06 electrons have a negative charge
G07 the magnitude of charge on all electrons is the same
G08 the nucleus has a positive charge
G09 the nucleus contains one or more protons
G10 protons are positively charged
G11 the magnitude of charge on all protons is the same
G12 the magnitude of charge on protons and electrons is the same
G13 the nucleus may contain one or more neutrons
G14 neutrons have no charge (are neutral)
G15 atoms have no overall charge (are neutral)
G16 atoms contain equal numbers of protons and electrons
G17 the nucleus is located at the centre of the atom
G18 the electrons occupy one or more 'shells' surrounding the nucleus
G19 electron shells are filled started with the innermost one (K), then L, then M ...

G20 the maximum number of electrons in the innermost (first, K) shell is two

G21 the maximum number of electrons in the second (L) shell is eight

G22 the 'type' of atom depends on the atomic number (number of protons in the nucleus)

G23 elements contain only one 'type' of atom

G24 atoms often bond/join together to form molecules

G25 a compound has molecules with several types of atom

G26 some atoms tend to donate one or more electrons to form a positive ion (cation)

G27 some atoms tend to accept one or more electrons to form a negative ion (anion)

G28 some electronic configurations (structures) are associated with stable (unreactive) atoms

G29 full outer shells (noble gas configurations) tend to be associated with stability

G30 atoms usually have stable electronic configurations when bonded

G31 covalent bonds are formed when atoms 'share' electrons (by overlapping 'shells')

G32 ions tend to form into lattices (crystals)

G33 lattices (crystals) are neutral overall

G34 the ratio of cations to anions in a lattice depends upon the ratio of anion charge to cation charge.

G35 ionic (electrovalent) bonds are formed when oppositely charged atoms (anions and cations) are attracted together

G36 the periodic table is related to electronic structure

G37 the elements in period one only have electrons in the first shell

G38 the elements in period two have electrons in the first two shells

G39 the elements in period three have electrons in the first three shells

G40 the elements in group 1 (alkali metals) have one electron in the outermost (occupied) shell

G41 the elements in group 2 (alkaline earths) have two electrons in the outermost (occupied) shell

G42 the elements in group 7 (halogens) have seven electrons in the outermost (occupied) shell

G43 the elements in group 0 (8, noble/inert gases) are stable and do not readily form bonds

G44 the number of bonds an element can form is called its valency

G45 an element's valency is related to it's position in the periodic table

G46 elements in group 1 have valency 1 (electrovalency of +1)

G47 elements in group 2 have valency 2 (electrovalency of +2)

G48 elements in group 7 have valency 1 (electrovalency of -1)
G49 compounds between non-metallic elements have covalent bonding
G50 compounds between a metal and a non-metal tend to have ionic bonding
G51 non-metallic elements usually comprise of covalently bound molecules
G52 the charge on ions depends on the valency of the element
G53 metallic elements have their atoms arranged in lattices
G54 a metallic lattice comprises of cations and 'free' (delocalised) electrons
G55 covalent substances are usually low melting
G56 covalent substances are usually insulators
G57 covalent substances are usually insoluble (or not very soluble) in water
G58 ionic substances tend to be hard
G59 ionic substances tend to be high melting
G60 ionic substances tend to be insulators when solid
G61 ionic substances tend to be conductors when fused
G62 ionic substances tend to be soluble in water
G63 solutions of ionic substances (in water) tend to be conductors
G64 metals tend to be quite high melting
G65 metals tend to be quite hard
G66 metals tend to be shiny
G67 metals tend to be workable (malleable, ductile)
G68 metals tend to be insoluble in water
G69 metals tend to be good electrical conductors

Appendix 6.

Syllabus content.

This thesis concerns students' developing understanding of chemical bonding during an A level course. Reproduced below is the subject content for the most relevant section of the A.E.B. A level syllabus for examination in 1994. (The colearners in the study followed the A.E.B. syllabus, and the largest number of them - including Tajinder, see chapter 8 - took the examination in that year.)

Subject Content	*Guidance Notes*
	The examination will be set not only on the syllabus but also on the guidance notes which indicate the breadth and depth of treatment required.
1. *STRUCTURE AND BONDING*	
(a) ***Atomic Structure:***	
(i) Fundamental particles: electrons, protons and neutrons.	
Atomic number, mass number, relative atomic mass and the 12C scale for relative atomic mass.	Calculation of relative atomic or molecular masses from simple mass spectra. Isotopes. Elementary treatment of mass spectrometry.
(ii) Flame spectra of s-block metal chlorides. The line spectrum of atomic hydrogen as evidence for electron energy levels.	An awareness that $\Delta E = h\nu$, but no calculations will be set.
(iii) Electrons as particles. Elementary treatment of quantum numbers and atomic orbitals.	An awareness of the wave properties of electrons and the use of electron diffraction in the determination of structure.
(iv) Relationships between atomic structure, ionisation energy and the Periodic Table.	Plot of successive ionisation energies for a particular element to introduce quantum numbers. Plot of standard molar first ionisation energies against atomic number to introduce sub-shells.

(v) Radioactive emissions: alpha and beta particles and gamma radiationThe exponential decay law; half-life and its determination; radioactive dating.	An awareness of a connection between nuclear structure and the stability of isotopes but no detailed treatment of mass deficit and mass excess is required. The relationship between the type of emission and the mass and atomic number of the daughter nuclide. Plots of activity against time used to determine half-lives and solve numerical problems. Brief description of the application of radioisotopes to the dating of archaeological and geological objects.

(b) *Bonding and Structure:*

(i) Ionic bonding. Factors influencing its formation: ionisation energy, electron affinity and lattice energy. Characteristic properties of compounds which are predominantly ionic.	A qualitative appreciation of the effects of ionic charge and ionic radius on the magnitude of lattice energy for simple crystals.
(ii) Covalent bonding. The covalent bond considered as electron pairing or as the overlap of atomic orbitals.	End-on and sideways overlap of atomic orbitals (σ and π-bonds) will not be examined.
Characteristic properties of substances which are predominantly covalent.	The properties of both small and large covalent molecules should be considered: e.g. iodine and diamond.
Van der Waals' forces.	The existence of weak short-range intermolecular forces responsible for bonding in molecular crystals: no treatment of the origin of these forces is required.
Bond polarity, electronegativity and inductive effect. Homolytic and heterolytic fission. Nucleophilic and electrophilic attack respectively, on positive and negative centres in molecules.	
(iii) Multiple bonding.	e.g. ethene, benzene, nitrogen and carbon dioxide.
(iv) Shapes of simple molecules; explained by repulsion between bonding and non-bonding electron pairs.	Typical shapes exemplified by CH_4, NH_3, H_2o, HF, BCl_3, PF_5, SF_6, Co_2.

(v) Hydrogen bonding. The hydrogen bond illustrated by contrasting the structure and physical properties of H_2O with H_2S, NH_3 with PH_3, and HF with HCl.	Comparison of strengths of various types of bonds (using tables of physical constants)
Hydrogen bonding in alcohols, carboxylic acids, proteins and DNA.	A brief qualitative treatment only.
(vi) Metallic bonding: qualitative description of the delocalised bonding in metals, leading to a simple explanation of the characteristic properties of substances which are predominantly metallic.	The model for a metallic lattice of positive ions in a 'sea' of mobile electrons will be sufficient. To include electrical conductivity.
(c) *Crystals, Structures and Associated Properties:*	
(i) Structures of metals: close-packed and body-centred.	Alkali metals as body-centred; copper as close packed. Distinction between h.c.p. and c.c.p. is not required.
(ii) Ionic lattices: exemplified by sodium chloride and cæsium chloride.	Comparison of the NaCl and CsCl structures and the cation: anion radius ratio as one factor in determining lattice type.
(iii) Covalent lattices: simple molecular and macromolecular structures.	e.g. iodine, and carbon as diamond.
(iv) Relationship between physical properties and structural type in solids.	Properties such as hardness, melting point and electrical conductivity.

Appendix 7.

Learners' ideas in topics prerequisite to chemical bonding.

§A7.0: The purpose of this appendix.

Chapter 3 of the thesis reviews previous studies into learners' understanding of chemical bonding (§3.2), and surveys research into children's ideas in several topic areas seen as necessary prerequisite knowledge for learning about bonding (§3.1). This appendix provides additional details of the literature in these prerequisite topics.

§A7.1: Learner's ideas about matter and chemical substances.

§A7.1.1: Specific conceptions about matter.

A number of studies report examples of alternative conceptions about matter and the chemical substance concept.

The *Learning in Science Project* included a study "to investigate children's conceptions of what is happening when water boils, evaporates, and condenses, and when ice melts" (Osborne and Cosgrove, 1983, p.826). The interview-about-events procedure was used with 43 school pupils aged from eight to seventeen years. Some of the conceptions elicited from the interviews were investigated further by a survey of 725 pupils in the twelve to seventeen age range. In the survey respondents were presented with descriptions of the events used in interviews, and asked to select from alternative explanations based on the interview responses.

Bar and Travis (1991) report a study based in Jerusalem which used an open-ended oral test (interview) procedure with 83 pupils in the 6-12 year age group, followed by a written objective test administered to 152 10-14 year olds, and an open-ended written test taken by 266 11-15 year olds. As part of the work of the *Children's Learning in Science Project* (CLiSP), Briggs and Holding (1986) focussed on aspects of secondary students' understanding of elementary ideas in chemistry. They analysed scripts collected as part of the *Assessment of Performance Unit* national survey, and undertook a small scale interview study. Their informants were aged 15 years. Another CLiSP study investigated the progression of learners' ideas about air, by using an interview-about-events procedure (similar to the interview-about-instances approach, see chapter 4, §4.6.2) with school pupils at ages 5-6, 8-9, 12 and 16 years (Brook and Driver, 1989).

§A7.1.2: Learners' conceptions of gases.

Brook and Driver found that many five year-olds only recognise the existence of air when there are perceivable air movements, e.g. a draught (1989, p.50); many school pupils do not realise that air takes up space (p.50), and think that air does not have any weight or has negative weight (p.51).

§A7.1.3: Learners' conceptions of boiling.

School pupils have been found to think that when water boils the bubbles are made of air; of oxygen and/or hydrogen; of water, or water and heat, or heat; or of smoke (Osborne and Cosgrove, 1983, p.827; Bar and Travis, 1991, p.372). The CURRICULUM SCIENCE option - that when water boils the bubbles consist of steam - was the least popular choice of four offered to 12 to 15 year olds (Osborne and Cosgrove, 1983, p.829, fig.1). The notion that bubbles may be made from heat reflects Engel Clough and Driver's finding that both *heat* and *cold* may be considered as if material substances, even by secondary phase pupils (1985, p.179).

From a scientific viewpoint the identification of the bubbles in boiling water, and the identification of the material leaving a kettle, and being condensed on a nearby cold object would seem to present the same problem. However, for those not holding the scientific conceptions, there is no *prima facie* reason to expect they would see these phenomena as directly related.

Students' conceptions include suggestions that the stuff coming out of boiling water is smoke; changes into air when it is no longer visible; is air; or is water and heat; as well as the CURRICULUM SCIENCE response that the stuff coming out of boiling water consists of the same particles as in the water (Bar and Travis, 1991, p.371-2, Osborne and Cosgrove, p.828-9).

§A7.1.4: Learners' conceptions of evaporation.

From a scientific viewpoint evaporation is closely related to boiling, but to the non-scientist these may be observed as very different phenomena, or as synonymous - thus the expectation that "water should *evaporate* at 100 degree Celsius" (student in class of 13-14 year olds, Wightman *et al.*, 1986, p.237).

Alternative conceptions about evaporation reported in the literature include evaporation means making milk thicker; water evaporating is perceived as passing into the surface, even if the surface is non-porous like a plate; water that evaporates simply ceases to exist; water that evaporates changes into air; water that evaporates splits up into hydrogen and oxygen; and that on evaporating vapour collects near the ceiling, as if the room acts as a container for the vapour (Bar and Travis, 1991, p.369-370; Edwards and Mercer, 1987, p.48; Osborne and Cosgrove, 1983, p.831-2).

Bar and Travis report that ideas about evaporation tend to pass through stages,

> "development takes place through a set of consecutive hierarchical stages in the age range 5-12 years. These are: (a) the water disappeared, (b) the water penetrated the floor, (c) the water evaporated into a container, and (d) the water evaporated and scattered into the air."
> (Bar and Travis, 1991, p.364.)

Bar and Travis point out that "the correct interpretation of the process of boiling is attained by children younger than those who correctly explain the process of evaporation [as] many children know that water changes into a gas by the process of boiling, but they do not understand that the same change can occur by evaporation" (Bar and Travis, 1991, p.371). They suggest this is because in the case of boiling "the phase change from liquid to gas can be seen and heard, the source of energy is directly observable, and the process is relatively rapid" (pp.377-378).

§A7.1.5: Learners' conceptions of condensation.

Explanations for the condensation formed from steam on a cold surface elicited from learners include condensation was a kind of sweat; steam makes a plate wet (i.e. this is considered a sufficient explanation); steam changes back into water, but it might be different water - not the kind we drink; condensation is due to heat loss (*i.e.* this appeared to be considered a sufficient explanation); the condensation occurs when hydrogen and oxygen recombine (Osborne and Cosgrove, p.829-30).

In a survey question about condensation on a jar of ice, the explanation that oxygen and hydrogen from the air had formed water was selected by over 30% of respondents at all ages investigated (12 - 17 years) and was the majority view for respondents aged 12 through 15 years (fig.3, Osborne and Cosgrove, 1983, p.834).

When there is no obvious source for condensation, the responses given in interviews follow a different pattern. (Again similar phenomena - as interpreted from within a scientific framework - are not necessarily perceived by learners as closely related). Bar and Travis point out that in this case learners need to appreciate that air contains water vapour even when there is no obvious source (1991, p.378). Learners' explanations, when there is no obvious source for the condensation, include water appearing on the outside of a jar of ice has come through the glass; or has been produced by the coldness coming through the glass; the coldness changes into water - selected by between 25% and 50% of pupils over the ages 10-14 years; the cold surface and dry air react to form water; and the coldness causes hydrogen and oxygen to change into water - about 30-35% of 10-14 year-olds selected this explanation (Bar and Travis, 1991, p.375; Osborne and Cosgrove, 1983, p.833).

The curriculum science explanation that the water in the air sticks to the glass attracted less than 20% of respondents surveyed at ages 12 - 14 years, and less than 25% of those aged 15 (Osborne and Cosgrove, 1983, p.834). Bar and Travis point out that awareness of the notion of condensation is not sufficient for a scientific explanation to be given for condensation phenomena,

> "Only the assumption that vapor exists *in* the air can lead to the conclusion that vapor *from* the air had condensed on the cold vessel and caused the appearance of water drops on its outer side. ... most participants are aware of the process of condensation. They know that vapour can be changed into water. But knowing and being able to use this knowledge ... appears to cause difficulties except for only a very small percentage of the participants."
> (Bar and Travis, 1991, p.376, italics in the original.)

Bar and Travis relate learners' difficulties in understanding scientific ideas about evaporation and condensation to the difficulty in accepting the existence of invisible substances. For example they note that the proportion of learners suggesting bubbles in boiling water contain air actually increases with age as they come to accept the reality of air in the room. They also suggest that the visible clouds of condensation droplets near a kettle may be misidentified as water vapour, which allows the learner to accept the existence of such vapour in the air, so that "the ability of young children to conceive a phase change during boiling is related to identifying [the white cloud] as vapor at a stage when they cannot yet conceive unseen matter" (Bar and Travis, 1991, p.378).

§A7.1.6: Learners' conceptions of melting and liquids.

Among ideas elicited from learners to explain melting are that ice just melts, i.e. this seems to be be perceived as sufficient explanation; ice melts because it is above its melting temperature; and ice melts because particles move further apart; and that melting is the same as dissolving (Osborne and Cosgrove, 1983, p.834; Wightman et al., 1986, p.47). Liquid may be equated with *watery*, as when one of the students in Wightman's case study asked "is liquid metal mainly water?" (p.305).

§A7.2: A model for describing progression in understanding chemical substance.

Learners' ideas about matter have been explored by Renström, Andersson and Marton, who interviewed 20 Swedish pupils in grades 7-9 (i.e. 13 - 16 years of age) about their "understanding of one of the most central questions in chemistry: the nature of matter" (1990, p.555).

In their earlier work with pupils in these grades they had met "ways of reasoning that seemed to be profoundly at odds with the ways of reasoning that teaching in science is supposed to develop (and takes for granted at higher levels)" (p.555). They had found a number of alternative conceptions of physical phenomena:

- over half of 13-16 year olds thought boiling means that air leaves the water (in the form of bubbles);
- some understood boiling as disintegration of water molecules;
- less than half of students thought that gas was a kind of substance with weight and mass;
- others thought heat is hot air - and hence has weight.

The identification of the properties of a substance with its molecules is well documented in the literature, and will be explored in more detail below (§A7.4.1). The distinction between energy and matter (e.g. heat and air), and the conservation of substance on a change of phase (i.e. that gases are still material, and that boiling water leads to another form of the *same* substance) are usually considered as more fundamental notions.

In their interview study Renström and coworkers used nine common materials as foci for discussion: salt, iron, aluminium, wood, water, oil, air, oxygen and carbon dioxide. They had a prepared script of questions, but also followed up the range of responses on an individual basis. The analysis of interview protocols followed what they called "a nonalgorithmic, interpretative 'discovery procedure'..." (Renström et al., 1990, p.557) leading to a description of possible ways of thinking about matter (p.558). Six distinct 'conceptions of matter' were identified, although individual students did not necessarily apply only one of the conceptions: "the same student can very well adopt different conceptions as a background for reasoning about different problems and different substances" (p.558, c.f. discussion about context and multiple frameworks in chapter 2: §2.3.5; §2.4.2; §2.5.1).

The six conceptions were

(a) a homogeneous substance - the substance is not delimited from other substances and it lacks substance attributes.
(b) substance units - the substance is delimited from other substances and it exists in more than one form (which creates the potential for thinking of phase transition).
(c) substance units with 'small atoms' - small particles are introduced. They may be different from the substance in which they are embedded (which creates the potential for thinking of atoms, which are components of the substance but do not have its macroproperties).
(d) aggregates of particles - the substance consists of infinitely divisible particles, which might not consist of the substance.
(e) particle units - the substance consists of particles that are not divisible into other particles and that have certain attributes (such as form and structure) that may explain macroproperties of the substance.
(f) systems of particles - the substance consists of systems of particles. Different macroproperties of the substance can be accounted for in terms of particles and particle systems.

(Renström et al., 1990, p.558, p. 560, pp.565-566.)

Renström, Andersson and Marton considered these six conceptions to form a hierarchy (p.558) in terms of increasing explanatory power and more detailed understanding (pp.565-566).

The first conception has very little explanatory power. Substances that are considered homogeneous are not changeable, and so phase changes are meaningless. Boiling is therefore seen as a process involving a second different substance,

> "...the two substances that are combined to form one must have some kind of parallel existence. Water and air were believed to exist as homogeneous masses in all other substances. Oil, for instance, might be understood as comprised of water and fat. The students believed that when water boils it is the air in the water that escapes. Salt contains water and it is this water that runs out if salt melts."
> (Renström et al., 1990, p560.)

Even less dramatic changes in properties, such as heating, may be explained by considering the changed (e.g. warmer) material to be a different substance, so that "students who expressed this conception had great difficulty in ascribing attributes to the substance" so for example "for them there appeared to exist three different types of air ('gases'): air, hot or warm air , and cold air" (Renström et al., 1990, p.560). They gave the example of a ninth grade pupil who reported that "Air cannot be heated. Air is air. Warm air is warm air" (p.560). 13 - 16 year olds holding this conception of matter would find notions of chemical bonding between atoms of no relevance, and would be unable to learn about bonding in a meaningful way.

As one progresses through Renström et al.'s scheme the increasing sophistication of the conceptions begins to approach the CURRICULUM SCIENCE notion of matter,

> "the six conceptions of matter should not be seen as a set of one correct and five erroneous conceptions. At each level some new insights are added that cumulate to the kind of understanding aimed at: Substances are delimited from each other, the same substance can have different forms; component parts of the substance may not have the qualities of the substance; substances consist of particles, the particles have certain attributes and are not infinitely divisible; and macroproperties of the substance can be accounted for in terms of particles and particle systems. All these various insights are packed into 'the correct' understanding of matter. In a way we can see our investigation as laying free or making visible the various tacit, taken-for-granted layers of the (scientific) understanding of matter."
> (Renström et al., 1990, p.568.)

However, even those learners operating at the most inclusive level of the hierarchy (that "closest to that aimed at in chemistry teaching" where "matter was conceptualized in terms of particle (or subparticle) systems and the relations between particles", pp.563-564) did not demonstrate a conception of matter which could explain all that is expected by age 16. So even the most sophisticated conception uncovered was not a 'final stage'. Renström and coworkers point out that none of the learners considered the space between particles in their explanations (pp.564-565).

§A7.3: Elements, compounds and mixtures.

In chemistry samples of matter are divided into three ontological categories:

- elements - which are pure substances which can not be broken down into anything simpler by chemical means.
- compounds - which are pure substances which can be formed from, or broken down into, several elements.
- mixtures - which are not pure, and may be separated by physical means such as filtration, distillation etc.

In practice these definitions are not always easy to apply.

In terms of a particle model:

- elements are considered to comprise of only one type of atom (*i.e.* atoms with the same proton number - the qualification 'considered to' is used as it is arguable whether the 'atom' concept is appropriate in, say, molecular hydrogen, or metallic lithium: see chapter 12, §12.4.7, §12.5). E.g. hydrogen only contains nuclei with proton number 1 and sodium only contains nuclei with proton number 11.
- compounds comprise of one type of molecule (*i.e.* molecules comprised of a particular configuration of nuclei of particular proton numbers), or a lattice with a repeating arrangement of such a configuration. Compounds have defined stoichiometries: *e.g.*, water comprises two parts hydrogen to one part oxygen, where the parts are measured in terms of the number of nuclei present.
- mixtures contain several types of particle at the molecular level, and do not have fixed stoichiometries.

Understanding of atoms and molecules (see the previous sections) provides learners with a basis for appreciating both the distinctions between elements, compounds and mixtures, and the significance chemists give to these categories.

§A7.3.1: Learners' conceptions about elements.

Briggs and Holding (1986) analysed a sample of responses by 15 year olds to a national survey carried out by the Assessment of Performance Unit (A.P.U.), and then undertook an interview study with pupils of this age.

They found that only a small proportion answered questions about elements using the ideas of CURRICULUM SCIENCE (p.23, p.27). They uncovered a range of alternative ideas, including the notions that elements can not be split into anything except by chromatography; an element is a type of solid, and sometimes a solid that gives off a gas when burnt; an element *can* be split into two or more substances; elements make other elements; elements need oxygen to stay living (c.f. §A7.6); an element would only give one product on electrolysis; an element will not dissolve in water; an element - unlike a compound - is a natural material; an element is a mixture, and that water is an element (Briggs and Holding, 1986, pp.19-21, pp.29-30, p.32).

§A7.3.2: Learners' conceptions about compounds and mixtures.

Briggs and Holding also found that some of the 15-year old students interviewed had alternative conceptions about compounds and mixtures, or at least imprecise use of the terms.

Alternative notions included the idea that compounds are 'mixtures of elements'; a mixture contains more than two elements, whereas a compound contains only two elements; all oxides are impure; something is impure if it has more than one [type of] atom in it; and that the stoichiometry of a compound can vary (Briggs and Holding, 1986, pp.52-54, p.77).

The students were not necessarily using the term 'mixture' in its scientific sense: one student went on to explain how the mixing would "change the chemicals inside ... rearrange them"; and another thought a compound was "a kind of mixture where there's two or more elements *joined* together or *bonded* together forming a different substance" (p.52, present author's emphasis). It would seem that an appropriate interpretation in these cases is that the students do not sufficiently distinguish the terms 'compound' and 'mixture', rather than they think the word 'compound' means what a *chemist* would call a 'mixture'. For one respondent the difference between a *mixture* and an *impure* substance is that "you don't want it to be" *impure*, but "you mean it to be" a *mixture* (p.56). (Although this is an anthropocentric definition, it probably reflects something of the everyday use of the terms.)

§A7.4: Learners' understanding of particle theory.

Renström, Andersson and Marton's 1980 study, discussed above (§A7.2), found six conceptions of matter - which could inform "an instructional progression toward the development of consecutive layers of understanding" (Renström et al., 1990, p.568), or in other words could be viewed as related to the atomic hypothesis of CURRICULUM SCIENCE to varying extents.

Particles were part of their second conception in the hierarchy, but such particles "were not believed to be atom like, but rather concrete pieces of varying size: drops of water, grains of salt and so forth." (p.560). In the third conception "small atoms" or "small particles of some kind" (p.560) are *embedded in* the substance. However these particles are made up of the substance itself. In the next (fourth) conception the substance unit *consists of* small particles. These particles were still sometimes considered to *contain* the substance, and to have no particular attributes, and they had no particular size. Indeed particles were believed to infinitely divisible - presumably as the pupils had learnt that "everything consists of particles" and 'everything' must include the particles themselves "leading to the somewhat paradoxical conclusion that atoms consist of atoms" (p.562).

Even at the next level, Renström et al.'s fifth category, where "the particle is not further divisible into other particles, and ... it has certain characteristic attributes" (p.562), some students still thought the atoms consisted of the substance, so that "when the water freezes the molecules freeze" (p.562). Renström, Andersson and Marton concluded that "although science teaching may enlarge the student's vocabulary - insofar as they use terms like 'atoms', 'molecules, 'chemical compounds', and so forth - it changes their views of the world around them to a very limited extent" (p.567).

Nussbaum and Novick have discussed difficulties in learning the particle model, with particular reference to the gaseous state (1982). Their studies had demonstrated that teaching had led to a belief in the particulate nature of air, at a heuristic level. However, questioning revealed that many learners could not accept a vacuum between the particles: suggesting instead that there was ***more of the substance*** between its particles. Although they had faithfully learnt the presented model up to the point where it contradicted their naïve continuous model, they then reinterpreted the particle ideas, so that they "assimilated new information, namely that air is made of particles, into their own alternative framework of continuous matter" (p.190). Griffiths and Preston also found that over one third of their sample of 16-18 year old students believed matter exists between atoms (1992, p.617).

One of the learners interviewed in a study by Ault, Novak and Gowin demonstrated Nussbaum and Novak's point. Andrew, a 2nd grade student, demonstrated conceptions consistent with Renström and coworkers's third stage (Renström *et al.*, 1990, p.560, see above) where "small atoms" or "small particles of some kind" are ***embedded in*** the substance. For Andrew the number of molecules increases from solid to liquid to air - contrary to normal notions of particle density. However Andrew's conception made sense within the framework described by Renström et al.'s 3rd stage. From this perspective Andrew considered that there is not much room for molecules in plaster, but that there is plenty of room for molecules in air. For Andrew, liquids contain water *and* molecules (Ault et al., 1984, figure 5, p.454.)

This finding is reflected in data from other research. Wightman writes of students reporting the outcome of a group discussion - on why solids, liquids and gases should be as they are - in a class of 13-14 years. One of the suggestions elicited was that on heating "the *substance in between the molecules* vibrated" (Wightman et al., 1986, p.195).

One of the learners, David, had written in a pretest before formally studying particle theory that "nothing is between the particles" of a gas (Wightman et al., 1986, p.148). Yet in the post-test he left this item blank, despite drawing a representation of a gas as fairly widely spread particles (his diagram showed too high a density of particles, and too evenly spaced, but was acceptable at this level, having inter-particle distances of many particle diameters, and no lattice type arrangement). When he was then interviewed he reported that "I think between gas particles there's just more gas particles" (Wightman et al., 1986, p.149). Wightman explored this notion with David, and he introduced the idea that there might be smaller particles from another gas that would fit in the spaces (although the spaces in the diagram he had drawn in the post test would have accommodated large gas particles), and actually described an ordered array: "I think it might be larger gas particles with small gas particles round and then large one, small, large one, small like that" (Wightman et al., 1986, p.149).

David was referring to his notion of air where "different gases have different size particles". Wightman focussed David's imagination on a pure gas, where he agreed all the particles would be the same, and she again asked him what would be in between them. Despite his diagram David reiterated his earlier conception that there were *more gas particles* between the gas particles,

> "I think more particles are between, more gas, gas particles ... I don't know why I've drawn it like that, I just imagine dots all around as particles all over the place."
> (Wightman et al., 1986, p.149.)

David seemed to have learnt the accepted diagram, but not to have reconciled this representation with his belief that particles would fill up the spaces. Another student justifying the belief that there were 'more atoms' between the atoms [sic] in air explained,

> "Because we said everything's made up of atoms and you can't have spaces where ... there's nothing, can we? Because everything's made up of atoms you've got to have more atoms."
> (Wightman et al., 1986, p.228.)

Another student interviewed by Wightman, Lynn, seemed unsure of what might be between particles. Between the gas particles in air was "nothing", which was "just air", which was "something that's made up of particles". Lynn was not sure what might be between the particles in a sample of pure oxygen, but offered "air" and "oxygen and gas" (Wightman et al., 1986, p.150). Wightman comments that possibly Lynn's later answers might be more concerned with attempting to respond to the questioning, than reflections of deeply held views. However, presumably, her eclectic responses reflect some uncertainty. That Lynn equated "nothing" with "just air" reflects the findings of Renström and colleagues (reported above), that less than half of secondary students in their studies thought that gas was a kind of substance with weight and mass. For students who do not consider gases to be material, explaining gases in terms of molecules may be premature.

§A7.4.1: 'Macro-micro confusion.'

The particle model of matter is used by scientists to explain the features of substances experienced in the laboratory, and everyday life. These features are observable: yet the model itself consists of hypothetical particles on a very much smaller scale.

The terms 'macroscopic' and 'microscopic' are sometimes used to distinguish these scales: alternatively 'molar' and 'molecular' may be used. 'Microscopic' is perhaps an unfortunate term as it seems to imply the particles in the theory are observable under a microscope. (Although modern techniques - such as scanning tunnelling microscopy - have produced photographs 'of' atoms and molecules, these are pictures of computer generated images interpreted from non-visual data, and are something quite different from the magnified visual images that learners will have seen through the optical microscope.) The particle theory explains the observable macroscopic (molar) properties of matter in terms of the conjectured properties of the microscopic (molecular) particles. It is a successful approach *because* the properties of molecules are conjectured to be so different from the properties of bulk materials: molecules of a substance may be considered as identical, they are not subject to frictional effects (and gravity may usually be ignored), they undertake perfectly elastic collisions, etc. As is clear from the work of Renström, Andersson and Marton discussed above, this is a point that learners - only familiar with the molar level of their experience - often seem to miss. Some learners seem content to use forms of explanation which do no more than shift the explicandum from the macroscopic to the microscopic level. An example would be a student explaining that a substance melts because the particles from which it is made melt.

In practice there are a number of concepts that apply to bulk matter, but not to the particles from which they are conjectured to be made: *e.g.* pressure, temperature, melting temperature, boiling temperature and (for at least some materials) colour are intensive properties that only apply to the substance, but not its constituent parts. (Some extensive properties such as mass, weight, charge apply at both levels.) Ben-Zvi, Eylon and Silberstein found that nearly half (c.46%) of a sample of 300 Israeli high school students (aged about 15 years, and having studied 6 months or more of chemistry) ascribed inappropriate properties of a material to its individual atoms: properties such as electrical conduction, malleability, colour, odour and reactivity (Ben-Zvi et al., 1986).

This distinction, which gives many learners difficulty, is relatively recent in the history of science,

> "Properties have been conceived as arising either from the presence of property-bearing constituents of the substance, or from the arrangements and motions of the constituents. The former view, well established in Aristotle's (384 - 322 B.C.) doctrine of the four elements and in the doctrine of the Three Principles of Paracelsus (1493 - 1541), was challenged by the latter view in the 17th-Century revival of Greek atomism by Robert Boyle (1627 - 91) and other mechanical philosophers. *This school differentiated between the primary physical properties of the corpuscular constituents and the secondary chemical properties of bulk matter.* Nevertheless, until the establishment of a working definition of the element and the development of a rigorous form of qualitative analysis in the early 1800s, chemists continued to explain specific properties such as combustibility and acidity by the presence of property bearing constituents. it is echoed in the use of functional groups in organic chemistry."
> (Brock, W. H., in Bynum et al., 1983 (1981), p.343, present author's emphasis.)

Research has uncovered a number of alternative conceptions of molecules that can be related to students failing to appreciate the differences between the macroscopic world of their direct experience, and the conjectured nature of the 'molecular world' - macro-micro confusions:-

§A7.4.2: Learners' conceptions about molecules: meaning of 'microscopic'.

As mentioned above, the term microscopic may be an unfortunate one. Griffiths and Preston undertook an interview study with 30 grade 12 students (age 16-18) with varying science backgrounds in Canada, and itemised 31 misconceptions about molecules, and 21 about atoms. Amongst these were the notions that molecules could be weighed, and that atoms were visible under a microscope (Griffiths and Preston, 1992, pp.616-617).

Ault, Novak and Gowin - from one of the few studies having a longitudinal base - report one second grade student who managed to assimilate the taught concept of particles with his existing knowledge, so "apparently, Andrew accepted the proposition that molecules, like air, could not be seen, but he integrated that knowledge with his own concept that *you can't get close enough to see them*" (Ault et al., 1984, p.453). However, another of their second grade informants, "revealed ... [s]he equated molecules with visible dust ... She had coupled the notion of particles in matter acquired from instruction to her awareness of the smallest pieces of things directly observable" (p.453). A seventh grade student in their study, Cindy, suggested that one can not see steam because molecules are too far apart (figure 8, p.458).

Wightman reports from a classroom where the teacher was holding a plenary session after a class of 13-14 year olds had been working in groups - brainstorming ideas about solids, liquids and gases. The term 'molecule' was introduced by one student, and the teacher substituted 'atom' (a point considered later, §A7.5). He asked what the students understood by atom. 'Helen' suggested "particles", which were "things which make up something". When the teacher asked if there was any difference between these particles (i.e. atoms) and the particles (i.e. grains) making up a sugar cube, Helen thought they were the "same kind". Later she reiterated this, justifying her belief in terms of nomenclature: "they're the same - when you say atoms are particles then they must be t'same - can't have two different sorts of particles."

A consequence of Helen's ideas about the scale of particles was her notion that atoms in different material would be "different shapes", so that in a glass window the atoms were "long and sort of squarey shape with straight sides" because "whatever shape it's in the particles are that shape." For Helen, if there were circular atoms in a piece of glass "the sides won't be straight" (Wightman et al., 1986, pp.258-259). Another student had suggested that the atoms were "microscopic", meaning "you can't see them without a microscope - they're so small" (pp.195-197).

In another case study class Wightman reports that some of the 13-14 year olds "tended to use the word particle and crystal synonymously" (p.40), and that in the demonstration of Brownian motion using a smoke cell some pupils thought they were *seeing* the *gas* particles (p.57).

In a group discussion recorded by Wightman there was an in-depth consideration of molecules vibrating. One pupil, Matthew, seemed to find the whole notion of vibrating molecules dubious, and argued his point by considering breathing, as "if molecules vibrate - then what about when we're breathing - they get warm in our lungs - they don't start vibrating then" (p.287). One of Matthew's peers apparently accepted this argument, and another countered that the lungs were not "*very* warm", and that the vibration came when "it's boiling" (p.287). The assumption that one would be able to perceive the vibrations if they occurred was not challenged.

§A7.4.3: Learners' conceptions about molecules: frictionless motion.

Friction and air resistance are macroscopic phenomena, explainable in terms of particle theory. The particles themselves do not experience friction. However, in their study Nussbaum and Novick found that "the idea of constant inherent particle motion is not internalized by many students, even among those who claim that gases are made of particles" (1982, p.190, c.f. §A7.7.4).

Wightman asked 13-14 year old students who had been studying particle theory if they had any questions about the topic. Two of the responses were "why do the atoms move and what keeps them moving?" and "if you have - a nuculus is it, and there's all them protons [sic] and whatnots circling round it, what keeps them going?" (quoted in Wightman et al., 1986, p.305). In a written test response a student in this case study referred to how air could be compressed in a syringe, but when one "let go of the plunger the air atoms [sic] started moving around again" (p.314) apparently implying that the motion had ceased. Indeed in another case study Wightman found that the common demonstration of Brownian motion using a smoke cell - intended to provide evidence for the motion of air molecules - was misinterpreted by one student. 'Craig' thought the demonstration was "ace", but the particles were, "not really moving are they? They're not really moving. ... It's just light reflecting and making them look as if they're moving" (p.58). As will be seen later (§A7.7.4), the notion of continuous motion without some obvious source of motive force is counter-intuitive for most learners.

The notion of particles vibrating also gave students some difficulties. One student group observed by Wightman had an in-depth discussion over this possibility (pp.286-291), at the end of which members of the group expressed considerable uncertainty over how the particles could start vibrating (p.291). When Wightman later asked them about this point, one pupil suggested that "the heat doesn't so much get the atoms moving, as break down the bonding", but another concluded that "it's summat to do with the innards of the atoms ... it might be a trigger inside the atoms" (p.288).

§A7.4.4: Learners' conceptions about molecules: integrity of matter.

Solids often seem dense, rigid and 'full of stuff'. Yet, particle theory suggests that solids are composed of particles that may be considered something like 99.999 999 999 9% empty space. (Matter that does not have this space is believed to exist - in neutron stars for example - but is considered 'super-dense' by our standards.)

Griffiths and Preston found that some students conceptualise molecules as *composed of* solid spheres (1992, p.616), and that for some students atoms are said to *resemble* solid spheres (p.617). Again this is inappropriate as the term 'solid' is another that loses its meaning at the level of describing individual molecules.

§A7.4.5: Learners' conceptions about molecules: individuality of atoms and molecules.

All molecules containing the same arrangement of the same set of nuclides are indistinguishable.

Taking for an example a binary compound of two elements that are only found with one stable isotope each: all molecules of AsF_3 would have the same mass (and therefore weight), and would be the same 'size' (however one might define this for a molecule) and shape etc. (The qualification regarding isotopes is strictly necessary as elements occur in different isotopic forms, which means that molecules of a particular substance may have different masses: *e.g.* Cl_2 may be ^{35}Cl-^{35}Cl {mass 70u}, ^{35}Cl-^{37}Cl {mass 72u}, or ^{37}Cl-^{37}Cl {mass 74u}, where u is the unified atomic mass unit, i.e., 1.7×10^{-27} kg.) Different molecules in a sample might be in different energy states, but this is transient - electrically excited molecules would spontaneously relax, and energy of vibration and rotation would be exchanged readily due to interactions ('collisions') between the molecules. However, for some learners molecules of a substance may vary in several ways. Griffiths and Preston found students in their sample thought they may be different in terms of the elements contained, the number of atoms, their size, their shapes, and their weight (1992, pp.616-617). Ben-Zvi and coworkers found two thirds of their sample of Israeli high school students thought that atoms of the same substance have different properties if from the solid rather than the gas (Ben-Zvi et al., 1986).

Whereas it is important for learners to appreciate the indistinguishable nature of atoms and molecules of a particular type, it is just as important to understand the distinctions between atoms of different elements, and molecules of different substances. Griffiths and Preston also uncovered student beliefs that *all* atoms are the same size, and *all* atoms are the same weight (1992, pp.616-617).

According to CURRICULUM SCIENCE the *average* speed of the particles of a substance is related to the temperature of the substance, and pupils are taught that increasing temperature (on the macroscopic scale) is interpreted as the molecules moving faster (at the microscopic level). Griffiths and Preston however report students believing that molecules *within each phase* move at the same speed (1992, p.617).

§A7.4.6: Learners' conceptions about molecules: the effect of heating substances on molecules.

In scientific terms heat is defined as energy in the process of being transferred due to a difference in temperature. As temperature is a macroscopic state function, it therefore follows that heat is only a meaningful term at the molar level. It is an oxymoron to talk of heating molecules.

Yet this distinction has been found to be difficult for learners, and the notion of heating molecules leads to consideration of the effects of heat *on* the molecules. For example Griffiths and Preston report that some students believe molecules and atoms expand on heating (1992, pp.616-617). Briggs and Holding report that some 15 year-old students explained the change in volume during a chemical change in terms of the particles expanding due to applied heat (1986, p.65).

Wightman reports interviewing two students who had just observed an experiment demonstrating thermal expansion in a metal rod. One explained "I think, atoms expanding ... The atoms are expanding. ... The atoms are expanding, with the heat they are expanding." The second student then offered an alternative explanation, "it's breaking the bonding", after which the first pupil agreed, "yeh, they're breaking the bonding, they're moving further apart". This pupil now said that by 'expanding' he had meant the atoms "were pulling further apart" and ***not*** that "they were growing bigger" (Wightman et al., 1986, pp.252-253).

The interviewer then asked them about another experiment they had performed on thermal conduction - heating one end of a metal rod, and feeling the other end. The students had already talked to the teacher about this, and the second student started to explain conduction in terms of the scientific model they had been given by the teacher, "the heat was making the bondings weaker so they were vibrating. Then it knocked the ones next to make them vibrate, and then they vibrate all along ... Moving and knocking the next ones so they move ..." The first student then interjected the alternative suggestion, "*or* they could be breaking apart and *getting bigger*." The interviewer asked whether the atoms were getting bigger or just moving apart. The student responded that they were "just moving apart so there's bigger gaps in between" (Wightman et al., 1986, p.253).

In this conversation one pupil repeatedly suggests that atoms expand on heating, but then withdraws the proposition. Two possible explanations might be that:

- as in the examples from other research, reported above, his initial conception was that the atoms physically expanded, but he had become aware that this was not the teacher's preferred explanation. Perhaps he was deferring to 'authority', but unable to completely dismiss his original idea.

- alternatively, perhaps there was a genuine communication problem, and the student's recantations should be taken at face value. If the particles move further apart, and take up more space, this could be seen to imply they get bigger.

The distinction that it is not the particles that expand, they just move apart, is part of CURRICULUM SCIENCE. However, a strong argument could be made that this is just a linguistic convention, and that, (a) if a material expands on heating; and (b) yet it is made up from the same number of particles; and (c) there is nothing between the particles; then the effective volume of the particles has increased, and when the volume of something increases we usually call this expansion.

Another pupil in this study refers to the atoms in the bar (being heated) "expanding and spreading out". The interviewer sought clarification, and asked "what's expanding?" to which the pupils responded "the atoms in the bar". However, when asked "does that mean the atoms are getting bigger?" the pupils replies "no *they're just spreading out*" (Wightman et al., 1986, p.257). The distinction that CURRICULUM SCIENCE emphasises here is one that seems to rest on a model of atoms as non-compressible solid spheres. To a chemist the atoms in a metal are bonded together (through the overlap of atomic orbitals to form molecular orbitals) and there is no space between the atoms. From this perspective it can be argued that the atoms certainly do expand when the material is heated. However from a CURRICULUM SCIENCE perspective the particles do not expand when a substance is heated: the particles move further apart, and the *substance* expands.

It could be argued that this is a pedantic distinction: (as suggested above) when the substance expands, the average volume of space taken up by each particle is more. Alternatively, the material density decreases, but the particle masses are unchanged, so particle volumes must have increased. From this viewpoint the particles have increased volume, so they are larger, so they have expanded. The distinction between 'the particle itself' and the space 'it takes up' may be sensible if our model of particles is one of the incompressible spheres imagined in elementary kinetic theory of gases. However in chemistry we will need to build a model of 'fuzzy atoms' that can overlap, and that fade away rather than cut out. In chemistry the size of an atom is usually given as a radius. The radius of an iodine atom in iodine is either 133 pm or 215 pm (1 picometre = 1×10^{-12} m) depending on whether one is interested in its separation from the atom it is covalently bonded to, or its separation from atoms in other molecules.

Standard classroom experiments that demonstrate thermal expansion give no basis for distinguishing between expanding particles, and greater inter-particle separation. Wightman comments on the notion of particles changing size which recurred in her study, that "this idea of the particles themselves getting larger was chosen seemingly because the notion of them becoming further apart with nothing between was unacceptable" (Wightman et al., 1986, p.72).

Wightman reports a pair of students working on the same circus of experiments, who disagreed on how to interpret thermal expansion in terms of particles. One initially suggested "the atoms are expanding in the heat", but then had an alternative idea, that "the heat's pulling the atoms further apart" (p.256.) The other pupil thought the atoms "*must* be getting bigger", but the first pupil had decided that was wrong. The reasoning was based on the types of explanations the teacher had been using up to then,

> "[atoms being pulled further apart] sounds more logical *from what we're doing* because *we've been doing about* the atoms going towards each other and away from each other, but *we haven't been doing about* the atoms getting smaller"
> Wightman et al., 1986, p.257, present author's emphasis.

This type of approach - the "guess what's in the teacher's mind" strategy, perhaps (c.f. §2.8.3) - did not prevent other students in the study using the alternative conception that "when the air particles cool they get smaller" (post test written response, Wightman et al., 1986, p.153).

According to the particle model, it is not the molecules which change when a substance is heated, but their arrangement. For example phase changes do not change the molecules - except in terms of energy states. However, Griffiths and Preston found some students thought that water molecules in ice were larger than in the liquid, which were larger than those in steam (1992, p.616). Some students also thought that molecules break down on heating (pp.616-617). One of the students in Ault, Novak and Gowin's study, seventh grader John, suggested that phase change was due to a change in molecular hardness (1984, p.459). Wightman reports a discussion between a group of 13-14 year olds where it is suggested that when a gas is formed the particles "grow lighter" (Wightman et al., 1986, p.276). In another group the suggestion was that on heating "the molecules themselves shrink - contract ... become less dense and turn to gas. And when they freeze - they expand - become more dense and turn to ... a solid" (pp.290-291).

One of the students in Wightman's study, Joanne, initially (in a pretest) explained butter becoming soft when left out of a refrigerator on the basis of changes to the butter particles: in the cold "the particles are solid", but "as the temperature rises the particles in the butter expand"; although she also thought that on melting the the "butter particles leave other particles". After the taught material (i.e. in the post-test) Joanne had developed a more scientific model: there was no mention of particles expanding, but rather "heat making the particles move about" and in the liquid "the particles can now flow [sic] about past each other". However, Joanne explains the mechanism in terms of the "particles bonding ... being *melted*" - her language still describes molecular events in terms of molar phenomena (Wightman et al., 1986, p.320).

Another student in the study, Nigel, also wrote in the post-test that "the weak bonding in the butter particles *melts*" (p.331). Yet another of the students, Helen described how when aluminium was heated in a Bunsen burner flame, "it melted because when particles are put forward to heat *the bonding melts*" (p.331). According to another student, when butter was heated in a frying pan some butter particles would "expand *too* quickly and be trapped underneath the other ones and be burnt before they can escape" (p.331).

In several places in Wightman's study students give different responses in interviews to those they have produced in written answers - to the extent that at one point Wightman questions the validity of the written responses as indicators of what students think (Wightman et al., 1986, p.317). An example is found with David who in both the pretest and post-test explained butter melting by ascribing to molecular particles inappropriate molar behaviour: "the butter particles expand when the temperature rises" and "as the temperature rises, the butter particles start to melt" respectively (p.157). In an interview, after the post-test, David confirmed that his response had meant that the particles themselves change, however that was not what he now thought,

> "I think just the attraction force between them starts to change. The attraction force like on a solid the attraction force is great, but on, in a liquid it's not as great, the attraction force. ... [That the particle itself melted was] what I put down *there* but *now I think* that the attraction force between particles was not as great..."
> (Wightman *et al.*, 1986, p.158.)

§A7.4.7: Learners' conceptions about molecules: explaining mechanical properties (e.g. density and hardness) in particle terms.

The difference in density between gases and condensed matter is understood in terms of the particle spacing. However, one of the students in Wightman's study - Nigel - had an alternative interpretation, in terms of differences in the particles themselves,

> "I seem to think of the air atoms as being sort of larger than the water ones and not quite as strong ... whereas the water ones are much sort of smaller and more compact."
> (Wightman et al., 1986, p.323.)

Nigel also explained the 'spring' of the air by transferring the property to be explained to the particles,

> "The atoms are obviously quite springy and that when they're compressed - y'know like when you compress a ball it sort of springs back out t'shape again. ... [the atoms get] crushed sort of together and start being - deformed."
> (Wightman et al., 1986, p.323.)

As discussed above, learners may often explain thermal expansion in terms of the particles themselves expanding, and Nigel followed this trend,

> "I think that when it gets warm you see during the day, the particles will somehow grow to make [a football] harder so it's denser inside. So it'll grow so that they're larger making the thing larger itself inside. And yet at night, when it gets cool, they sort of shrink again, and the ball hasn't got as much to fill it inside so it sort of flops down a little bit."
> (Wightman et al., 1986, p.329.)

If the particles were to expand without a change in mass this should lead to a decrease in density, but it is possible that Nigel is conflating density and hardness here. He explained butter going soft by transferring the property to the butter particles,

> "what must happen is that the particles themselves get softer and so can't hold their shape quite as well. Get much softer, so they're not as hard ..."
> (Wightman et al., 1986, p.331.)

A pupil in Wightman's other case study class explained a soap film in terms of particles "stretched out ... to fill the shape ... They stretch out and make bigger" (p.72). This could be another example of the phenomena to be explained being directly transferred to become a property of particles, or it could be a lack of differentiation between the two levels of description. Cheryl talks of "the atoms" in the soap film "sort of like stretching out together" and then refers to "it all" expanding": *it all* was then defined as "particles, and t'atoms and soap film as well" (p.105).

However another pupil in this study, David, was quite explicit that he thought compression of air did involve changes in the particle size,

> I: Can you tell me more about why you actually can compress air?
> D: You can compress it because the air itself, the particles can go smaller and each particle can go into a smaller space than the larger ones.
> I: Mm. Each particle can go smaller?
> D: Yes, if pressed smaller.
> I: The actual particle can ...
> D: Yes.
> I: can get tinier?
> D: Yes.
>
> D: David; I: Interviewer
>
> (Wightman et al., 1986, p.142.)

§A7.4.8: Learners' conceptions about molecules: appearance.

Griffiths and Preston found that some of their sample reported that atoms and/or molecules were flat. A number even suggested that an atom looks like several dots and circles (1992, pp.616-617). Of course the absolute size of atoms, and the range of wavelengths of visible radiation mean that it is not possible for atoms to directly 'look like' anything. These young people seem to have taken aspects of diagrams representing atoms more literally than is appropriate.

Wightman reports a student comment in a lesson,

> "We're all saying atoms are round - I don't think they are. Nature made things [searched for a word] convenient. Round ones don't fit together."
> (Wightman et al., 1986, p.229.)

This student's notion of atomic shape is apparently based on a teleological principle that atoms would be 'designed' to fit together.

§A7.4.9: Learners' conceptions about molecules: the relationship with macroscopic terms for substances.

Briggs and Holding found from interviews that some 15 year-olds do not have a clear understanding of how the terms used to discuss matter at the macroscopic and microscopic levels are related. This is perhaps understandable as the main distinction at the microscopic level is between atoms and molecules. At the macroscopic level chemists distinguish mixtures, compounds and elements - all of which are comprised of molecules, which in turn are understood to be 'made up from' atoms. The other main distinction made is between solids, liquids and gases - but for a particular substance these are explained in terms of the same molecules. One student thought an element was "just one part of an atom" (p.50), perhaps confusing 'element' with 'electron'; another suggested that the elements were "different parts of a substance ... like in water there's oxygen" (p.50) - which seems to be referring to the atoms 'in' a molecule.

§A7.5: Learners' conceptions about the relationship between atoms and molecules.

Some of the alternative conceptions reported in the literature do not seem to be directly related to transferring macroscopic properties to the microscopic entities of the theory, but rather suggest failures to learn fundamental aspects of the molecule concept.

When particle theory is first taught as a theory of matter, it is not usually deemed appropriate to distinguish atoms from molecules. Indeed the particles of interest are molecules, and it may be argued that at this stage the concept of atom is not needed. (Pressure is due to *molecular* bombardment, temperature is related to the average kinetic energy of the *molecules*, changes of state are explained as changes in the configurations of collections of *molecules* - as overcoming inter*molecular* forces.) The concept of the atom *is* used however to explain chemical phenomena (as well as nuclear physics), and learners need therefore to appreciate how atoms relate to molecules when explaining chemistry at the molecular level.

Unfortunately teachers may use 'atom' as a synonym for 'particle' in which case this may cause difficulties later. Wightman reports how in one lesson observed, "the teacher conjured up an image of diffusion in solutions by referring to blue copper sulphate 'atoms', and colourless water 'atoms' wriggling slowly past each other at the junction of the two layers" (Wightman et al., 1986, p.217). In another lesson the teacher referred to how "the atoms in solids are strongly bonded to neighbouring atoms", whereas in a liquid "the atoms are free to slide past each other" and are "weakly bonded", and in a gas "atoms are not bonded together" (p.224). Whilst this description might be appropriate for certain substances (neon, argon etc.), it is generally incorrect as the *atoms* would be strongly bonded *within molecules* in the fluid phases as well as in the solid state. The students being taught in this class - not surprisingly - picked up the teacher's use of the terminology, and in an interview with Wightman students told her that on boiling *the atoms* were "losing their bonding", and that they had "no bonding when they're in that steam" (p.238).

In this particular case the teacher had deliberately selected to use the word 'atom' rather than 'molecule' in the work on particle theory. After some work on the properties of solids, liquids and gases the students had been asked to work in groups to 'brainstorm' ideas about why the three three states were different. When the students began reporting back the first group immediately introduced the idea of molecules, and the teacher suggested the term 'atom',

> T You're talking about molecules. Can I write atoms instead of molecules - 'cos it's shorter? Thank you. Are we bothered about this? because ... some groups were talking about molecules and some groups were talking about atoms. Some groups were talking about 'balls' and some groups were talking about other things altogether. ... does it matter what we call 'em?
>
> Ps Yes - Yeh [general tone of surprise at the question]
>
> ...
>
> J 'Cos they're not always the same thing. Some might be smaller than others. ... People say theirs are made up of balls and other people say they're made up of squares and they've got to have a common name.
>
> T Well, look - we'll say that the common name is *atoms*, for the sake of argument. ...
>
> T: teacher, Ps: students in class, J: student 'Joanne'
>
> (Wightman et al., 1986, p.195.)

The teacher's decision to support Joanne's idea to use a common name seems appropriate, but in terms of subsequent use of particle ideas in chemistry, 'molecule' would have been a more helpful choice, albeit twice as long to write on the board. It is interesting to note that this was the same teacher who was reported in chapter 3 as responding to student questions about how the tendency to form bonds was overcome in gases as "something to do with chemistry" (Wightman, et al., 1986, p.216). The teacher justified his choice of word in his lesson evaluation,

> "Using the word 'particle' would appear to confuse the situation - particle is not a specialist term. Most particles met in real life are certainly not atomic in size - particles of soot etc. Better perhaps to use *ATOM* which does suggest something a little special. They have all certainly heard of the word and are not scared to use it."
> (Wightman et al., 1986, p.199.)

Griffiths and Preston report that some students in their survey thought atoms are larger than molecules (1992, pp.616-617). Although *some* atoms are larger than *some* molecules, this conception is inappropriate as a general rule as molecules are considered as stable groups *of* atoms. (Although this is a simplistic approach, see §12.4.5 and §12.5).

In Briggs and Holding's study they discuss an A.P.U. question where students were asked to identify elements, compounds and mixtures from pictures showing different types of particles in gases. Although 40% of respondents in their sample selected an appropriate diagram of 'a mixture of two elements', almost as many, 39%, selected a diagram showing identical particles (molecules) each comprised of two differently shaded sub-units (which the question informed them, represented atoms of different elements). 43% correctly selected this latter diagram as representing 'one compound only', but 33% of respondents instead selected a diagram showing identical particles (molecules) made up of two similar sub-units (atoms). As 74% of respondents appropriately selected this as representing 'one element only', some of the students must have chosen this figure to be both a compound and an element (1986, pp.39-41). Follow up interviews demonstrated the confusion some learners experience. One student thought that in a compound the atoms are the same (p.42), and another thought that a sufficient condition for an element was all the particles (i.e. molecules) were the same (p.43).

§A7.6: Anthropomorphism and animism; and atoms and molecules.

Particle theory enables the scientist to explain properties of bulk matter in terms of molecules which behave like perfect elastic spheres and which follow the simple principles of Newtonian physics.

Yet when many learners are asked to explain phenomena in terms of particles, they do so by imbuing the particles with the properties of living entities (animism), and sometimes with the feelings and intentions of people (anthropomorphism). For example, Griffiths and Preston found some 16-18 years olds expressed the belief that atoms are alive (1992, pp.616-617) - although, their conception of 'alive' need not be a scientific one. Of their 30 informants "ten subjects suggested that atoms are alive because they move" (p.623) - which would not by itself satisfy the biological criteria for life. Others expressed the view that "only some atoms are alive" and one thought that *organic* atoms are alive" (p.623). Piaget (§2.2.1) had explored children's animism quite early in his career, and suggested that "since the child does not distinguish the psychical from the physical world, since in the early stages of his development he does not even recognize any definite limits between his self and the external world, it is to be expected that he will regard as living and conscious a large number of objects which are for us inert" (1973 (1929), p.193).

Piaget proposed a number of stages through which such animism passed. However, in doing so - and in keeping with his programme of developing a genetic epistemology - he ignored idiosyncratic aspects of his data, such as that "many children's conceptions of consciousness embody certain attributes, such as the fact of having blood, of being able to speak, of being visible (for the wind)" (p.197). This caveat noted, Piaget suggested that,

> "From the results obtained, four groups may reasonably be distinguished, corresponding *grosso modo* to four successive stages. For children of the first stage, everything that is in any way active is conscious, even if it be stationary. In the second stage consciousness is attributed only to things that can move. The sun and a bicycle are conscious, a table and a stone are not. During the third stage an essential distinction is made between movement that is due to the body itself and movement that is introduced by an outside agent. Bodies that can move of their own accord, like the sun, the wind, etc., are henceforth alone held to be conscious, while objects that receive their movement from without, like bicycles, etc., are devoid of consciousness. Finally, in the fourth stage, consciousness is restricted to the animal world."
> (Piaget, 1973 (1929), p.197.)

Piaget himself warns that diagnosing which stage a child is at is problematic, for "it may easily happen that a child who has just attributed consciousness to to a particular object denies it directly after", so "care must, therefore, be taken not to regard any of the examinations as establishing an absolute individual analysis" (Piaget, 1973 {1929}, p.215). The transcript extracts presented do not seem to suggest common ages for the four stages: a twelve and a half year old is presented as one of the examples of a child at the second stage, where "the fourth stage is not reached on an average before the ages eleven to twelve, but several children of six to seven were found to belong to it" (Piaget, 1973 {1929}, p.212.) Piaget concludes,

> "Each of the children taken alone, might possibly show an implicit systematization different from that brought out by our questions, each is capable also of retrogressive movements in the series of stages just as much as of progressing in a straight line, but, on the average, the four types of answer obtained certainly constitute the types of systematization through which the child's spontaneous thought really passes, and these four types correspond to four stages."
> (Piaget, 1973 {1929}, pp.218-219.)

In terms of Piaget's analysis, atoms and molecules would be considered as conscious by those at the third stage - as bodies that can move of their own accord. One would expect most students at senior secondary level and above to have moved past this stage according to the evidence of Piaget's informants: however, Piaget's subjects have been found to often reach his stages of development early compared with wider populations (e.g. Beard, 1969, p.17).

Given these uncertainties:

- Piaget's exclusion of evidence relating to idiosyncratic rather that generic thinking;
- the vast (overlapping) age ranges at which the different stages were reported;
- the uncertainty of how the ages of Piagetian subjects relates to general populations;

- the contradictions within Piaget's interviews;
- the retrogressions of Piaget's subjects;

it may be unwise to assign *students* to stages. However the four stages do represent a useful typology of the degree of animism inherent in a *conception* for individual utterances.

An assumption behind Piaget's stages is that animism is something that a child eventually 'grows out of' (Crain, 1992, p.117). A different view was taken by Werner who looked at the same phenomena from the perspective of perception rather than primarily concept development. Werner compared what he called *physiognomic* perception and *geometric-technical* perception. The latter was perception in terms of objective properties (such as size and shape), whereas physiognomic perception involves reading expressive and emotive qualities into (non-sentient) phenomena (Crain, 1992, pp.85-89). In children this leads to animism. Although this mode of perception tends to be largely superseded by geometric-technical perception it does not disappear as a person matures: rather, it tends to be associated with the aesthetic sense. In some cultures (such as Native Americans) it was quite normal for the environment to be perceived pgysiognomically so that trees and rocks were said to have feelings. From Werner's perspective it would not be surprising to find evidence of physiognomic perception among adults (including young adults, such as A level students).

§A7.6.1: Animistic and anthropomorphic references to particle 'behaviour'.

Wightman undertook case studies of two secondary classes (of 13-14 year olds) studying the particulate nature of matter. In one of the case studies a pupil asks the teacher "are atoms alive?" The teacher's response seems to pay cognizance to Piaget's ideas,

> "I think the question about whether atoms are alive or not could almost throw us off onto the wrong scent. Atoms are not alive in the sense that er they can think or that they have any response, or that they have a blood system or a heart of anything like that [student]. But it seems that atoms *can* move about of their own accord - so they are capable of motion if you like."
> (Wightman et al., 1986, p.211.)

In the report of this work there are a number of examples of learners' use of animistic and anthropomorphic language,

- jumping: in a gas "when each particle is energised and so it jumps away from the rest of the particles..." (p.32).
- reproducing: gas particles "might be reproducing ... They might be making more. ... They could be spreading out but they could also be reproducing" (p.138).

- trying and wanting: air in a syringe is "trying to - pressing out on all sides - it wants to go as far as it can, ... it's trying to push [the plunger] up ..." (p.142). This extract was part of an interview about particles in a gas, but the student's comment above does not refer directly to particles. Another student interviewed, however, referred to "oxygen gas particles ... moving anywhere they want to go really" (p.149).
- holding hands: in a classroom discussion the teacher asked what kept atoms together in a solid. It was suggested they were linked. When the teacher asked 'how', it was suggested the atoms hold hands: although accompanying laughter suggested that the student was aware of the absurd aspect of this response (p.277). The teacher, presumably did not find the suggestion too obtuse, as he developed the image as an explanation of the difference between solids and liquids: "in solids they're linking arms - whereas in liquids they're only linking fingers" (p.278).

One of the most explicit uses of anthropomorphism reported in Wightman's study was actually not from a student, but from one of the case study teachers as he tried to encourage the class to think about what happened "in terms of the atoms" as he attempted to pull his metal key ring apart,

> "Can you imagine them inside there? Going ooh - ow as you try to - rip these neighbouring atoms apart right down the middle aagh - aagh!" (Wightman et al., 1986, p.214.)

The teacher also had students role-play atoms to model diffusion in gas (p.215), and referred to "copper sulphate 'atoms' [sic], and colourless water 'atoms' [sic] wriggling slowly past each other" (p.217).

§A7.6.2: Anthropomorphic references to explain thermal expansion.

Driver (1983) gives examples of 13-14 year-olds' classroom explanations of thermal expansion in a thermometer. Some of these seem animalistic, suggesting the mercury is conscious, so that "mercury rises up a thermometer tube, to get away from the heat. ... it stays till the heat is gone" (p.43), or even anthropomorphic, implying the actions of particles may be explained in terms of the types of feelings and motives normally reserved for people, so that "mercury *likes* to be cool so when it is heated the particles are *trying* to get away from the heat " (p.43, my emphasis).

The difficulty in interpreting these sorts of comments is that it is not clear to what extent words are used metaphorically. In the following examples the italicised words could be interpreted as implying that the 13-14 year old pupils imbue the particles with feelings, and conscious motives,

> "Heat is *making* the particles expand, they now *need* more space to move and so *push* upwards *making* the mercury rise as well."
> (Driver, 1983, p.43.)
>
> "the - erm - heat molecules are *giving* more energy so they *need* more room to move about ... the molecules *have* to expand"
> (p.44.)

However, it is also possible that in the absence of a full understanding of the 'mechanical' interpretation, the students are using the only language they have available. It is also possible that if such language is not challenged and questioned, then the students will *not* be motivated to find a deeper level of explanation. In the present study of the development of understanding of chemical bonding this will be a significant issue (see chapters 11 and 12). Piaget seemed to understand this point when he claimed that "the child's thought is much less self-conscious than ours, so that even such implicit systematizations as were found in the answers of the second stage, for example, are scarcely recognised by the child himself; they are due to an economy of reactions ... much more than to a deliberate effort to be coherent" (1973 {1929}, p.215). Indeed Piaget suggests that "in the child, animism is much more a general trend of mind, a framework into which explanations are fitted than a consciously systematic belief" (p.214).

One of the students interviewed in Wightman's study, Cheryl, also explained thermal expansion in anthropomorphic terms,

> "the particles are hot so they spread out and then when its cold they keep together ... the weather being warm the particles don't want to be hugged together so they've spaced out".
> (Wightman et al., 1986, p152.)

In some of the examples of anthropomorphic language considered above it was not clear if the students were talking metaphorically. However, in Cheryl's case, she does *not* use metaphor, but simile and analogy. That is, Cheryl is *explicit* that she is comparing particle behaviour to human behaviour (an analogy), and explaining particle behaviour *as if* it is due to human motives (i.e. simile),

> "it's more or less t'same but it's a bit, slightly different. ...Well I thought of it this way. ... it's *like* us, if we're all say crowded in that room, if it's warm we'll space out, but if it gets cold we'll all close in together. So that's t'way I see it."
> "they're closing together *as if* they want to keep warm. ... when it cools down they move together *as if* they were cold."
> (Wightman et al., 1986, p152, present author's emphasis.)

A7.7: Learners' ideas about mechanics.

> "It is now generally accepted that all of us, and students in particular, share a common intuitive explanatory scheme for phenomena. This 'intuitive physics', although we were not taught it at school, represents a partially self-consistent stock of concepts and relationships. It exhibits in some respects remarkable similarities to historical stages of physical theories."
> (Viennot, 1985a, p.432.).

Having considered what is known about how students conceptualise matter, and the molecules from which it is conjectured to be made, I now turn to another prerequisite topic, mechanics. Without conventional scientific conceptions of matter and molecules, it would be difficult to make sense of much chemistry. The argument for considering mechanical principles as prerequisites for learning about chemical bonding is less obvious, and indeed I am not aware of an explicit case being presented before. Where science is taught as separate disciplines the topics considered in this section would be classed as part of physics, not chemistry. Yet much of the explanation at G.C.E. Advanced level for chemical bonding and related topics - such as shapes of molecules, ionisation energies - relies on physical principles. These principles may often be taken as common ground, without explicit presentation, but without them the explanations have no basis. Questions such as

- what is a chemical bond?
- why do chemical bonds form?
- why are some bonds stronger than others?
- why are some bonds polar?

can not be answered from a scientific perspective without using physical principles. In particular a student studying Advanced level chemistry will need:

- distinct notions of force and energy;
- the idea of potential energy (i.e. electrical potential);
- an understanding of equilibrium of forces;
- knowledge about the attraction and repulsion between opposite (unlike) and similar (like) charges, and the awareness that charge is of two types (positive and negative);
- a notion of resultant force;
- the idea of electrostatic force diminishing in magnitude, with increasing separation of charges;
- the idea of electrostatic force increasing with the magnitude of the charges involved.

In order, then, for an Advanced level chemistry student to develop a consistent, integrated, conceptual scheme for understanding and explaining chemical bonding, he or she must be able to apply the physical concepts of energy and force with a fair degree of precision. Watts interviewed students over the secondary age range to find out how they conceptualised various situations in terms of these fundamental physics concepts. He was able to categorise responses in such a way as to identify eight frameworks for force (1983a), and seven for energy (1983b). Even when focussing on one particular type of force, gravity, Watts elicited responses that he described in terms of eight distinct frameworks (1982). These alternative frameworks reflect the scientific perspective to different extents.

As part of the A.P.U.'s National Surveys into performance in science questions relating to the concept of energy were answered by a large sample of school children. The *Children's Learning in Science project* analysed a representative sample of the data from 15 year olds (about 300 responses to each of 6 questions) to explore the ideas learners' used in answering the questions (Brook and Driver, 1984, p.24). Brook and Driver also undertook some interviews with 15 year olds (p.26). They concluded (p.106) from their study that,

- students tend not to use ideas about energy spontaneously to explain and interpret phenomena.
- high ability students who have studied physics are more likely to use accepted ideas about energy than students of similar ability who have not.
- students may experience difficulty in understanding energy as a quantitative idea.

These findings have consequences for the present study. The learners considered here are 16-18 year old Advanced level students, but if Brook and Driver's findings also apply to this group it might suggest that the background understanding for a conventional scientific model of chemical bonding may not be available to some of the learners. In this section then, the literature will be reviewed to explore what is known about learners' ideas about force and energy.

§A7.7.1: Distinguishability of force and energy.

From the scientific perspective, force and energy are distinct, and related in a tightly specified manner.

In everyday life the two words may be used interchangeably, and research suggests some learners do not have distinct concepts of force and energy. Watts and

Gilbert found that "a major feature of the many interview protocols analysed ... is the interchangeability of these two concepts" and that "some youngsters fail to distinguish between the two, others see them as distinct but inter-related and yet others as separate and unrelated" (1983, p.164). Where distinctions were made, they did not necessarily follow the accepted lines. For example, for one 16 year old physics student force was "something natural" whereas she "treats energy anthropocentrically: it is what people have in order to perform acts (like standing up, or running down a hill) of their volition" (p.166).

One of the alternative conceptions of gravity elicited by Watts was that "*Gravity increases with height*" (1992, p.119). Watts notes that a student's "description of 'gravity' seems to contain the germ of what a physicist would call 'gravitational potential energy' ..." (p.119). One of Watts' alternative frameworks for forces was labelled 'operative forces' where "force is an action. The amount of force is proportional to the amount of activity taking place". In regard to 'operative forces' Watts notes that, "physicists describe *energy* as the 'capacity to do work' a definition that seems remarkably similar to some of the pupils' definitions of force" (Watts, 1983a, p.227). Force is not only conflated with energy. Watts also found that "pupils ... were willing to treat velocity and speed as forces and to combine them with other forces (like gravity or air resistance) in order to describe changes in direction or magnitude" (p.224). Another of his frameworks for force was labelled 'impact forces' which "is a model of forces very similar to the concept of 'momentum' in physics" (p.225).

Brook and Driver found that "some students' associations for energy are not part of an accepted science view of energy. For instance, some students strongly associate force and movement with energy, but few students associate energy with the scientific concept of work" (1984, p.108). They reported that "students seemed to appreciate the distinction between the 'everyday' meanings of work and the scientific meaning more easily than they were able to distinguish between the scientific notions of work and force" (p.152, c.f. Solomon's distinction between life-world and scientific thinking, §2.7.1). As Viennot says "in spontaneous reasoning students are usually not conscious of the 'notion' they use and may call it, sometimes indifferently, 'force', 'impetus', 'energy', 'momentum' and so on" (1985a, p.433).

The research evidence shows then that 'energy' and 'force' are often not clearly distinguished by learners. This is a potential [sic] problem for a student trying to learn about chemical bonding. Put simply, the notion of force is needed to explain why atoms and molecules should bind together, but the concept of energy is also needed to understand how bonds may be broken - for example on evaporation.

§A7.7.2: Learners' ideas about energy.

Energy is not only conflated with force, but Solomon has shown that learners have other everyday, 'lifeworld', meanings for energy. Lower secondary students (i.e. c.11-14 years) suggested that "energy means power", and "energy is strength" (1992, p.42). Other associations of energv were with activity, life, being fit and healthy and breathing (p.43).

The lack of precision in such *lifeworld* meanings makes such notions of limited use for communicating ideas in science lessons. Solomon even found a gender difference in the predominate use of energy ideas: when learners were asked to write about energy the boys often focussed on sports and similar activities, and the girls often focussed on health. Solomon's analysis and interpretation of her data led to a number of common conceptions related to these themes, which she was able to juxtapose. I have tabulated these conceptions:

theme	energy and health	energy and activity
predominantly focussed on	by girls	by boys
common aspect	we all have energy	we all have energy
we need energy	to live	to move
we get energy from	rest and medicines	food we eat
when we lose energy we are	old, ill or we die	tired, or out of breath
exercise	builds up our energy	uses up our energy

(adapted from Solomon, 1982, p.48.)

It is interesting to note that the lifeworld view of energy is broad enough to encompass such contradictory conceptions as the suggested relationships between exercise and energy.

Brook and Driver (1986) report two case studies of classes (one of 13-14 year-olds, the other of 14-15 year-olds) studying energy as part of school science. They found that before formal teaching the learners tended to have anthropocentric associations for 'energy', so that "students initially associated energy with human activities; in the case of the younger class with human movement, in the case of the older class with food" (p.150). Brook and Driver also reported that the students in the observed classes did not clearly distinguish energy from matter,

> "A very obvious aspect of students' understanding in both cases was the tendency to see energy in a substantive way and to confuse material substances with energy forms. References were made, for example, to gas, motors, sun, swing energy and water energy in the first case study, and coal, oil and dynamo energy in the second."
> (Brook and Driver, 1986, p.150.)

I have previously pointed out that inappropriate labels are used in some school text books which imply such 'forms of energy', *e.g.* food energy, muscular energy, natural gas energy, tidal energy, volcanic energy, wind energy (Taber, 1989, p.59).

Brook and Driver report that concerning gravitational potential "there is a hint that energy was being seen as stuff stored like food in a cupboard" and that there "was also confusion about other ways of storing energy" (1986, p.151).

Although gravitational potential energy is of little *direct* relevance to understanding chemical bonding, it is quite common for atoms to be compared to 'little solar systems', with the expectation that the familiar gravitationally bound system will act as a useful analogy or model for the electrostatically bound atom. The assumption is that learners are familiar with the characteristics of the gravitationally bound system.

In one lesson a group of students were considering the energy changes when a weight fell from a bench to the floor. They decided that there was "more movement energy and less stored energy". However in order to explain why the weight should have more potential energy when on the bench they conjectured that there was *more force acting on it when it was higher up* (p.26).

Yet in another experiment as part of the same circus Brook and Driver report that students had difficulty recognising potential energy in a pendulum, because in their perceptions the bob had 'movement' energy throughout the oscillations (*i.e.* the learners were not able to consider the zero instantaneous speed at the maximum displacement). It was recognised that the bob was moving fastest at the lowest point, but this was explained in terms of a common alternative framework (discussed below) - that *the greatest force was acting at the lowest point.* On this occasion the force was identified with the push from the person setting the pendulum in motion, and for at least one learner the return swing did not need to be explained, so "the energy has pushed it there, but it didn't push it to come back" as "it just came, dinnit" (p.32). Brook and Driver's study reveals a number of common trends in learners' thinking: energy seems confused with force, force is perceived to be in the direction of motion, a force is only identified where there is human agency, and is not needed to explain what is clearly a 'natural' motion.

The notion of chemical potential energy may be seen heuristically as the energy released in chemical systems when reactions take place (and therefore understood to have been previously been 'stored' in the system.) A deeper analysis would show that 'chemical potential energy' is electrostatic potential energy: and its release is due to the reconfiguration of a chemical system so that electrons take up different arrangements with respect to each other and the atomic cores. The latter conception is clearly more abstract and complex. Evidence from Brook and Driver's case studies suggest even the former notion may be meaningless to those pupils who perceive stored energy to be substantive. During one lesson a student observed that "food *is* stored energy" (p.23, present author's emphasis). Holman refers to the familiar example of combustion of methane as an example of a chemical process releasing energy. He suggests the process may be represented on a simple energy level diagram with 'methane + oxygen' shown at a higher level, 'carbon dioxide + water' at a lower level, and the difference between the energy levels labelled as 'energy released'. He comments that "for some students, this is as far as the treatment should go, even though it stops short of explaining the ***origin*** of the energy that is released", and he explains that,

> Such an explanation requires an understanding of the processes of bond-breaking and bond-making, and these ideas are not easy. Indeed, for many students the treatment of chemistry may be best left on the macroscopic scale, and for them it is unnecessary to mention particles, let alone bonds. Even the more able students who have been introduced to the idea of molecules and bonds often find the energy changes involved in bond-making and bond-breaking confusing. They often seem to conceive of bonds as coiled springs, ready to unwind and release energy, rather than links which need energy to break them."
> (Holman, 1986, p.49, emphasis in original).

§A7.7.3: the relationship between forces and bodies.

Forces act on bodies, and cause changes in their motion (see below), but Viennot has noted that learners "do not often say *force acting on ... (the ball, the mass)*, but more likely *the force of the throw*, *the upward force you have given it*, *the mass has a force*, *the upward force of the mass*" (1985a, p.434).

One of Watts' frameworks for force was labelled 'designated forces' where the "force seems to reside within the objects" and is 'immanent', 'indwelling' or 'inherent' (1983a, p.222). The forces were associated with the perceived agent causing action i.e., "forces are designated to those objects that are causing or will cause events to occur" (p.223). The agent was often human, and people were perceived as "centres of force", which as Watts comments "is a very anthropocentric notion" (Watts, 1983a, p.223). As forces were designated to these agents, "some objects were seen as 'having' force, others were not", which resulted in students describing forces using language which Watts judged to be anthropomorphic (p.223).

Perhaps closely related to the notion of forces being seen as inherent in bodies (rather than descriptions of the interactions between bodies) was another of Watts' frameworks, which he called 'Substantial forces', where "forces are positive actions that are effective when they come into contact with objects" (p.227). Watts explained that here "the youngsters do not treat forces as acting along 'a line of application' or acting at a 'point of application'. For them forces are rather more expanded and wholesome" (Watts, 1983a, p.228).

Viennot advises researchers and teachers to be aware that they "may tap quite different reasoning when speaking of 'force *on* something', of 'force *of* something' or of 'force' not further specified" (1985a, p.435). She cautioned that the "spontaneous tendency ... to ascribe forces to objects" can lead to ambiguity on the point of which body is being acted upon by a force" (p.436).

§A7.7.4: Newton-1 and 2: inertia.

Three of the most important principles in mechanics are often known simply as Newton's first, second and third laws.

Newton-1 may be stated as: *a body will remain in a state of rest, or uniform linear motion, unless acted upon by a resultant external force.* Indeed the rest state may be considered a special case of uniform motion when velocity is zero: the significant point is not the velocity (or lack of it), but the *absence of change in velocity*. Within Newton's scheme rest and uniform motion are considered in the same way.

Newton-1 is actually redundant when Newton's second law is stated, as it is subsumed within. Newton-2 may be stated: *the rate of change of momentum of a body is directly proportional to the magnitude of the resultant force acting on the body, and takes place in the direction of the applied force.* It follows that if the resultant force is zero, then there will be no change in momentum: which is equivalent to Newton-1. For a constant resultant force, and in non-relativistic cases (i.e. speeds well below the speed of light: approx. $3 \times 10^{8}\ ms^{-1}$), Newton-2 , may be represented by

$$a = {}^{F}/_{m}$$

where a is the acceleration vector and F is the resultant force vector. m is the body's mass, which is said to be a measure of its inertia (i.e. "the property of a body by virtue of which it tends to persist in a state of rest or uniform motion in a straight line", Pitt, 1977).

One of Watts' frameworks for gravity was that "Gravity begins to operate when objects start to fall down and continues until they are at rest on the ground" (1982, p.119), which suggests that the force is only perceived as acting when it may be seen to be having an effect. This is related to one of his frameworks for force: 'motive forces' which "are required to cause and maintain the motion" (Watts, 1983a, p.225) so that "if a body is moving there is a force acting upon it in the direction of the movement. If a body is not moving there is no force acting upon it", although Watts notes that in applying the principle "some of the pupils ... make no distinction between force and net force" (p.226).

This particular framework seems to be very common, and has been associated with the historical notion of impetus. Gilbert and Zylbersztajn report that 85% of a sample of 125 14 year old UK pupils "associated force and motion". When asked about simple situations involving projectiles, "they saw the stone as having a force upward away from the person's hand as the stone moved upwards; the cannon ball was seen to have a force away from the cannon, moving it through the air" (1983, p.115). Considering the research evidence available, Gilbert and Zylbersztajn concluded,

> "The studies [reviewed] support the view that pre-Galilean ideas about force and movement are not only prevalent among school children, but also in certain cases do persist even after years of formal exposure to physics teaching. There is also evidence to suggest that, at least when projectile motion (vertical or composite) is considered, the conceptions are closer to the mediaeval impetus theories than to the older Aristotelian conceptions."
> (Gilbert and Zylbersztajn, 1985, p.117.)

These authors argue that "for most children, who are intuitive impetus theorists, ... inertial dynamics [i.e. the Newtonian framework] is anti-intuitive ... because it places uniform motion and rest on the same ontological level" (p.118). This viewpoint has been echoed by other workers. For example, Driver refers to a student who "seems to consider the natural state of any object to be the stationary state, and when the initial impetus given to the ball is used up it returns to this state" (1983, p.26). McCloskey (1983), finds the historical parallels curious,

> "Recent studies on the nature, development and application of knowledge about motion indicate that many people have striking misconceptions about the motion of objects in apparently simple circumstances. The misconceptions appear to be grounded in a systematic, intuitive theory of motion that is inconsistent with fundamental principles of Newtonian mechanics. Curiously, the intuitive theory resembles a theory of mechanics that was widely held by philosophers in the three centuries before Newton."
> (McCloskey, 1983, p.114.)

McCloskey and his coworkers undertook a series of studies with high school and college students, and found that "in many instances the students stated the impetus theory quite explicitly" - although using the lexicon of Newtonian physics, referring to momentum, or e.g. "the force that has been put into the ball" (1983, p.115). He reports that "Each major aspect of the impetus theory ... has its counterpart amongst the beliefs about motion that are widely held today" (p.115). Among the findings of McCloskey and coworkers were:

- about half of students asked thought a ball dropped by a moving person would drop vertically.
- over a third of students questioned though that a horizontally launched projectile moves horizontally at first, then curves, before finally falling vertically (and a few thought the horizontal motion changed to vertical motion suddenly as "gravity isn't going to effect it until it stops moving", p.119);
- thirty percent of college students asked expected an object with circular motion to continue to move in a curved path if no longer restrained (i.e. to have circular impetus, or "directional momentum... [which causes the ball to] follow the curve you've set it on until the ball runs out of the force within it that you've created by swinging", p.116);
- 93% of high school students tested demonstrated an impetus theory of motion before they were taught Newtonian physics, and "80% of the students retained this belief even after finishing the course" (p.122).

Viennot labels this common alternative conception 'V-F reasoning' as it may be modelled as $v \propto F$ (where v is the velocity and F the force), by analogy with the Newtonian principle that $a \propto F$ (where a is the acceleration). Viennot reports that when there is no force acting in the direction of motion learners will often invent one, and similarly, if there is no motion in the apparent direction of the applied force, a learner may invent a force to produce a zero resultant (1985a, p.434), as "the less satisfactory real forces seem to be to explain the motion, the more frequently they are denied and replaced, or supplemented by invented forces" (p.434).

§A7.7.5: Newton-3.

Newton's third law concerns what is commonly termed 'action and reaction', and may be stated: *when a body A exerts a force on a body B, then body B exerts a force on body A which is equal in magnitude, antiparallel in direction, and which acts along the same line of action.*

This is a principle that seems counter-intuitive to many learners. In a survey of third year secondary students (14 year-olds) using a 'pencil-and-paper' instrument

Watts and Zylbersztajn found that "82% of the pupils felt that if the person on the left is winning [a tug-of-war contest] then it is because that person is exerting a greater force *on the rope*" (1981, p.363, *italics* in original).

Even when they have 'learnt' the law, students may try to work round it. For example Driver described a student's response to a question about two carts being pushed apart by a compressed spring. The student was at the end of a teaching sequence on 'action and reaction' (*i.e.* Newton-3), and knew the principle, but perceived the two carts differently: "it's going to have another equal reactionary force, but that reactionary force still, for some reason - it's just as strong, but it doesn't have the same effect on it. It's effect isn't as strong". Driver comments that,

> Ricky is aware of the problem as involving the principle of action and reaction and even recognizes that the two forces should be the same. However, his intuitions suggest that the cart doing the pushing should behave differently from the one being pushed, and ultimately in making his prediction he trusts his intuitions."
> (Driver, 1983, p.39.)

§A7.7.6: Equilibrium.

The notion of equilibrium, when the resultant forces are zero, relates to a lack of acceleration. Yet in some situations an equilibrium of forces may be seen to lead to motion.

For example, if two equal, stationary, weights are connected by a rope which runs over a pulley, a difference in their height above the ground may be seen as sufficient cause for the system to shift until the weights are at the same height. In their survey of 125 third year secondary students Watts and Zylbersztajn found that "78% of the pupils thought that the objects, unaided, would move until both were at the same level" (1981, p.364).

Terry et al. (1985) found that secondary students had great difficulty identifying the forces acting on a static box resting on a table. Even among fifth year secondary pupils who had studied Newton's laws, almost half failed to identify any force exerted by the table. Some thought that the box was static because Newton's third law requires an equal opposite force (p.163).

§A7.7.7: Anthropomorphic and teleological reasoning.

When learners' ideas about molecules were reviewed earlier, it was found that students may explain the behaviour [sic] of particles in animistic or anthropomorphic terms.

Similar observations have been made about learners' explanations about macroscopic phenomena. Viennot has commented on 'dynamical terms' being ascribed to objects "in a rather animistic way" (1985a, p.435). One of Watts' frameworks for gravity had objects 'trying' to counteract gravity (1982, p.119), and one of his frameworks for force involved objects being "seen as inclined, or attempting, to produce action", so "for example, a golf ball in flight 'wants' to fall down, a bicycle 'wants' to slow down when the cyclist stops pedalling" (1983a, p.220, 'affective forces' framework). One of his frameworks for energy was labelled 'human centred energy', and Watts comments that "many of the descriptions that youngsters give when describing energy are very anthropocentric and anthropomorphic [as] they see energy to be associated mainly with human beings, or treat objects as if they had human attributes" (1983b, p.214). Another of the frameworks was called the 'depository model of energy', in which some objects were considered to be 'needing' energy (p.214). Terry et al. (1985) found that many third year secondary pupils (c.13-14 year in age) thought that inanimate bodies would not be able to exert forces (p.163).

Watts and Zylbersztajn, in their (1981) study with 14 year-old students, describe how (in accordance with V-F reasoning, see above) when explaining the motion of a stone thrown in the air, some students "mentioned gravity as featuring in all of the movement" whereas "for others it was seen as 'switching on' at the top". Gravity apparently waited until "the power [*i.e.* impetus from throw] has stopped". At this point "there is no force because it is at the peak of height and soon gravity will pull it down though not yet" (p.362). The students' comments reported by Watts and Zylbersztajn are noteworthy for more than their grounding in an impetus-like alternative framework. They also seem to have the following features:

- although force is related to motion, the implied causality is contrary to that one might expect: not that 'there is no motion because there is no force', but 'there is no force because there is no motion'.
- no mechanism is suggested for how gravity can 'switch on' at the appropriate moment, but the learner does not seem to find such 'switching' problematic.

Without more detailed explanations from the students, it is difficult to be confident in interpreting the student responses. However, such statements do lead to several tentative conjectures, which might be borne in mind when considering the data collected from my own interview study:

- student use of the word 'because' should not necessarily be taken at face value. *e.g.* does 'there is no force because there is no motion' mean?

(a) the reason there is no force is because there is no motion,
or
(b) the reason *I know that* there is no force, is because there is no motion;

- do students perceive certain states or phenomena as in some way natural, and requiring no further explanation. For example, when the impetus of a projectile has been exhausted, its natural place is on the ground, and gravity then acts teleologically to bring this about.

§A7.7.8: Forces and bonding.

Much of the literature on student ideas in mechanics would suggest that many learners would come to A level chemistry with alternative conceptions which are counter to the ideas needed to understand chemical bonding and related topics.

However one of the frameworks for forces proposed by Watts to represent student thinking was called 'configuration forces' - that is that "*objects restrained in a position have force*" (1983a, p221). Although this again demonstrates that force is verbalised as indwelling (see above), it does provide a basis for discussing bonding: if learners did not perceive a need for a force to hold objects in position then the concept of the chemical bond becomes redundant for them. A *configuration force* is "a notion of force as a 'bonding' between objects that hold them stable in relation to each other" and "without that bonding, objects would not be expected to stay in position, but would move apart" (p221). It should, however, be reiterated that Watts presented eight alternative frameworks for force based on his study, and the different frameworks represented the ideas of different students from within his sample: his work does not suggest all learners will have a notion akin to *configuration forces*.

Appendix 8.

Learning through talk.

In her first interview for the research Noor apparently constructed an explanation of intermolecular forces between neutral species. She had not been taught about this, and although her explanation is a little confused, this is a concept that many students find difficult, even when it is explained *to them*. This dialogue occurred just before the cassette tape was exhausted - thus my comments about checking on the tape.

N1.A553

1 I: Number 17, have you any idea what number 17 is meant to be?
• • • [pause, c.3s]
2 N: It's two iodine molecules, I'm sorry atoms,
• • •
N: no I'm not sure what that is.
3 I: So there's two iodine atoms,
4 N: Yeah.
5 I: and apart from that you're not sure?
6 N: They're bonded together somewhere
7 I: So where's there a bond?
8 N: Between the two,
•
N: semi-circles around them.
9 I: Ah right, so how many bonds do you think there is [sic] in the total diagram, the whole diagram?
• • •
10 N Twelve?
11 I: So is that inside each of these, 'peanut' shapes?
12 N: Yeah.
13 I: Yeah? So, is there any, any kind of bonding you think, between one 'peanut' shape and another?
14 N: Yeah there should be.
15 I: There should be?
16 N: Mm.
17 I: What kind of bonding would that be?
18 N: Think it would be charge, attraction between charges again.
19 I: Attraction between charges, so is that ionic is that?
20 N: No it won't be ionic,
I: Won't be ionic?
N: but it would be attracted to, the rest of it.
21 I: So they'll all be attracted together will they?
•
I: So which particles there are charged?
22 N: They won't be charged particles individually, but, but some will be slightly positive and others slightly negative, and that will cause, like a weak attraction, between them, holding them together.
23 I: So where might there be a slightly positive charge, whereabouts?
24 N: Erm if the electron,
• •
N: if the electron on one of them is nearer to the end, nearer to the,
•
N: if one electron's nearer to:wards the centre of the, iodine molecule and the other's further out, the one, bit where it's further out's going to be slightly more negative, than where it's empty. And so on the other side if it joins to the bit where it's empty, it's slightly positive, and so they'll attract, sort of, (~~something like that.~~)
25 I: That's interesting. I'll just have a quick look at how the tape is doing. Right, erm,
•
I: did you, has somebody told you that, or have you just thought of that, or is that something you've just sort of argued out, or that something that somebody's taught you?
26 N: That's what I think is going on anyway.
27 I: Sorry? {not hearing}
28 N: Just thought it out.
29 I: So nobody's ever told you that, you haven't sort of written that down ion a class somewhere, you just made that up, did you?
30 N: (Did I?) Yes!

Appendix 9.

Thagard's model of conceptual change.

§A9.0: Thagard's computational philosophy of science.

Thagard sees the personal construction of models of *alternative* scientific theories as a step in a rational process of paradigm shifts. Thagard's programme is to "understand the structure and growth of scientific knowledge", an endeavour he labels the 'computational philosophy of science' (Thagard, 1992, p.3). Although his work is based in historical case studies, Thagard believes his ideas may be applied to science learners. The scientist - or young learner - holds one theory, but gradually builds up an understanding of, and familiarity, with an alternative. If the alternative comes to be seen as having greater explanatory coherence then it will become the preferred theory with which to operate in that domain.

§A9.1: Alternative conceptual frameworks.

Thagard's work draws on scientific revolutions of the sort Kuhn (1970 {1962}) identified, but Thagard brings a perspective from Artificial Intelligence that conceptual changes may be modelled in computer programs. To do this he conceives of cognitive structure in terms of conceptual hierarchies. A main aspect of Thagard's work is that he considers scientific revolutions to be explicable in rational terms. His model is able to describe how scientific revolutionaries persuaded their peers to change their conceptual frameworks, as well as why some scientists held to their original frameworks. Thagard describes how a scientist exposed to an alternative theory (to the one held) will construct a model of the theory 'in the background' to compare with his or her original. The criteria for choosing between the theories are collectively referred to as 'explanatory coherence',

> "...the new conceptual system does not arise by piecemeal modification of the old one. Rather, the new one must be built up largely on its own, and its replacement of the old is the result of a a global judgment of explanatory coherence."
> (Thagard, 1992, p.60.)

For example when chemists learnt enough about the oxygen theory to believe it had greater explanatory coherence than the phlogiston theory, they changed to the new theory. For this to happen they had to be instructed in the new theory, but also had to have time to construct and explore, or read about and reflect on, the arguments in favour of the two alternative theories: "setting up the requisite nodes and links, was not enough: people had to use the new system enough to appreciate its power" (p.59). Thagard considers this to be a process which may take years. Priestley's rejection of the oxygen theory need not be considered as made on a non-rational basis, as he was "the preeminent phlogiston theorist" and "he had the most elaborate conceptual system for the phlogiston theory and, having used it more than others, the strongest appreciation of its coherence". Thagard suggests that Priestley "never used the oxygen system enough to fully appreciate that it was more coherent than the phlogiston system" (pp.59-60).

For our present purposes it is sufficient to note that during this scientific revolution scientists had to form alternative frameworks for understanding burning. Thagard suggests similar processes *may* be operating in children, and conjectures that "when they are taught more about biological and physical mechanisms they *consciously or unconsciously* appreciate that these accounts have greater explanatory coherence than their old theories and therefore abandon [them]" (p.258, my emphasis).

§A9.2: Degrees of conceptual change.

Like Novak, and Strike and Posner (see chapter, §2.10.1), Thagard distinguishes two types of conceptual change. He considers "merely adding a new set of ideas" and "replacement of a single concept or rule" as relatively trivial changes, and distinguishes these cases from 'revolutionary' changes which "involve the replacement of a whole system of concepts and rules by a new system" and are "much harder to understand" (p.6). For Thagard, "conceptual systems are primarily structured via kind-hierarchies and part-hierarchies" (p.7). His model of cognitive structure is the form of a network of concepts ("mental structures representing what words represent") connected by propositions ("mental structures representing what sentences represent", p.21), with the concepts making up the nodes of the network (p.30). It may be noted that such a model is open to representation in the form of 'concept maps' (§4.9.1).

Thagard uses five kinds of link:

- kind links which "indicate that one concept is a kind of another" (p.30).
- instance links which "indicate that some particular object ... is an instance of a concept" (p.31).
- rule links which "express general (but not always universal) relations among concepts" (p.31).
- property links which "indicate that an object has a property" (p.31).
- part links which "indicate that a whole has a given part" (p.31).

In such a model conceptual change is easily represented as "adding or deleting nodes and links" (p.32). Thagard's model has various "kinds of conceptual change, roughly ordered in terms of degree of increasing severity" (p.34) as,

- adding a new instance
- adding a new weak rule
- adding a new strong rule that plays a frequent role in problem solving and explanation
- adding a new part-relation
- adding a new kind-relation
- adding a new concept
- collapsing part of a kind-hierarchy, abandoning a previous distinction
- reorganizing hierarchies by branch jumping, that is, shifting a concept from one branch of a hierarchical tree to another
- tree switching, that is, changing the organizing principle of a hierarchical tree

(Thagard, 1992, from table 3.1, 'degrees of conceptual change', p.35).

§A9.3: Historical examples of conceptual change.

Thagard gives historical examples to illustrate his model. Adding a new part-relation, is called 'decomposition' (p.35). An example of this would be the decomposition of the atom [concept], when it was discovered not to be "an indivisible whole", but to contain electrons (p.35). Thagard (after Carey) distinguishes two types of process of adding kind relations, 'coalescence', "adding a new superordinate kind that links two things previously taken to be distinct" - such as seeing animals and plants to both be alive - and 'differentiation', "making a distinction that produces two types of things" - such as the distinction between heat and temperature (p.35). New concepts may be introduced in this way e.g. electromagnetism by coalescence of two previously distinct concepts of electricity and magnetism (p.35). Concepts can also be introduced into the conceptual system "for explanatory reasons": examples would be "oxygen, electron, quark and gene" (pp.35-36).

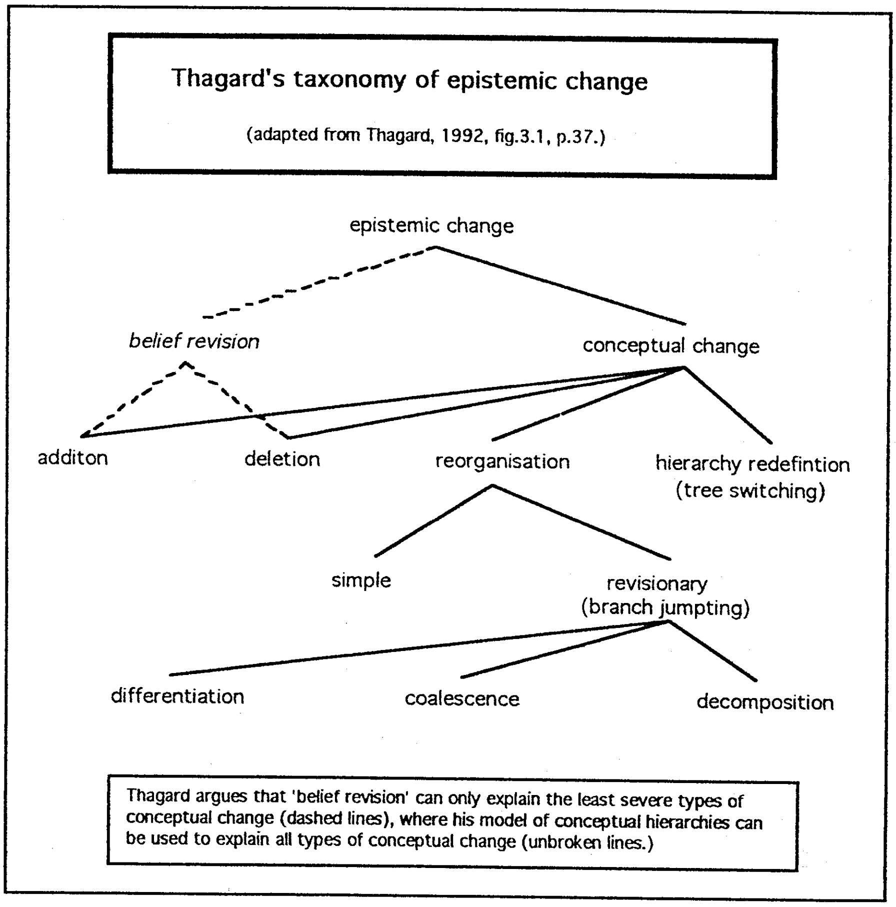
The reverse of differentiation is 'collapse' of the part-kind hierarchy - "the attenuation or abandonment of distinctions previously made" (p.36), such as "the distinction between species and varieties" (Darwin) and "the Aristotelian distinction between natural and unnatural motion" (Newton). As Driver has noted the ideas of children may often reflect the ideas of science in past times (1983, p.76) and Thagard's historical examples reflect the kinds of conceptual changes expected of science learners. Thagard suggests that all of these types of conceptual change may be understood as occurring by making specific (limited) changes to a conceptual system, and could be interpreted as belief revision.

Thagard argues that more profound changes have to be involved when conceptual ***revolutions*** occur. He gives examples of ***branch jumping***: "the adoption of Copernican theory required the reclassification of the earth as a kind of planet ... Similarly, Darwin recognised humans as a kind of animal, when previously they were taken to be a different kind of creature" (Thagard, 1992, p.36); and ***tree switching***, which may affect "the organizing principle of a hierarchical tree" which "is the most dramatic kind of conceptual change" such as when Darwin changed the meaning of 'kind' from just being similar, to "being of common descent" (p.36).

§A9.4: Thagard's typology of epistemic change.

Thagard suggests that "branch jumping and tree switching are changes that are very difficult to make on a piece meal basis" (p.36), and that they involve "moving concepts around in hierarchies and rejecting old kind-relations or part-relations as well as adding new ones" (pp.36-37).

His figure 3.1 (redrawn below) demonstrates this view.



§A9.5: Criteria for explanatory coherence.

Thagard suggests that "the most important relations between propositions concern explanation and contradiction" (Thagard, 1992, pp.8-9), and that "propositional systems are primarily structured via *relations of explanatory coherence*" (p.9, my emphasis). He claims that "many cognitive phenomena can be understood in terms of how rules with different strengths enter into *competition* with each other (p.56, italics in original).

Thagard's analysis of historical case studies suggests "a variety of factors that go into determining the explanatory coherence of a hypothesis" (p.63), and that alternative explanations 'compete' on such dimensions as,

- How much does the hypothesis explain?
- Are its explanations economical?
- Is the hypothesis similar to ones that explain similar phenomena?
- Is there an explanation of why the hypothesis might be true?

(p.63).

The first of these - "the explanatory breadth of the new theory" seemed to be the most important factor (p.248). However, greater familiarity with the existing theory and its potential applications may act as a barrier - it takes time and mental effort to explore the new ideas. This may include debate with peers, where "the process of argument and later reflection on it can lead to revision of conceptual links, enabling an alternative system to come to the fore" (p.59, c.f. the discussion in chapter 2 of the validity of Solomon's claims about the nature of classroom discourse in science lessons, §2.8).

§A9.6: The need for multiple frameworks.

An important aspect of Thagard's model - at least as far as the present research is concerned - is his acknowledgement that during major conceptual change "the new conceptual system does not arise by piecemeal modification of the old one" but "rather, the new one must be ***built up largely on its own***, and its replacement of the old is the result of a a global judgment of explanatory coherence" (p.60, my emphasis). The process may be summarised:

> "1. A [learner] with a theory embedded in a conceptual system becomes aware of a new theory that competes with the one already held.
> 2. Although initially skeptical, the [learner] sets out to learn more about the new theory, and gradually accumulates its conceptual system and an understanding of its explanatory claims.
> 3. The [learner] comes to appreciate that the new theory has greater explanatory coherence than the old one.
> 4. The old theory, and its attendant conceptual system, drop into disuse."
> (Thagard, 1992, p.104, with 'scientist' substituted by 'learner'.)

Thagard's model thus explains the epistemology of conceptual revolutions in terms of the *construction* of representations of *alternative theories* in a conceptual network. The kind-relations and part-relations that make up conceptual systems are also key aspects of an individual's ontology - "they specify the constituents of [the individual's] world" (p.32). Thagard's model, then, can also suggest answers to a question raised by Driver and coworkers: how "the range of objects that children take to exist in the world, i.e. their ontologies, extends and changes as children's reasoning evolves" (Driver et al., 1994b, p.89).

Appendix 10.

Colearner evaluation.

> "It was very intense, but afterwards I felt very good."
>
> (Tajinder's comment on one of the interview sessions)

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§A10.0: Extent of feedback collected from colearners.

Colearners interviewed during the period June 1992 to May 1994 were asked to complete a feedback sheet at the end of interviews. Feedback regarding 46 interviews was collected in this form over the period, involving twelve different colearners. (These colearners were Edward; Jagdish, Kabul, Lovesh, Mike, Noor, Paminder, Quorat, Rhea, Tajinder, and Umar; and a colearner Vivek, who provided data that was considered during analysis, but which did not provide any new insights, and is not quoted in the thesis (i.e. 'saturation' had occurred c.f. chapter 4, §4.4.1). One student was interviewed once, one twice, five three times, three four times, one six times and one ten times.)

Colearner Tajinder was actually interviewed on 23 occasions, as well as undertaking Kelly's repertory test several times. He felt that completing the same feedback form was tedious, and agreed to an alternative suggestion of switching to noting his thoughts in a brief diary. Some of his comments are considered below (§A10.3).

§A10.1: The questions asked.

The feedback had two parts. In the first colearners were asked to select from a long list of sixty words, those that described their feelings during the interviews (see the box below). Such a long list was used as I was not familiar with any previous work using this approach in a similar context, and I wished to include synonyms that the colearners would be familiar with covering possible reactions at the physiological, affective and cognitive levels. (In terms of Maslow's hierarchy {e.g. Dobson et al., 1981, p.255} I was concerned that the interviewees were physically comfortable enough to concentrate on the sessions, as well as not feeling intimidated or threatened so that they would feel able to respond freely.) The words were presented in alphabetical order, and were intended to include feelings that I considered both appropriate and undesirable. The colearners were also asked to add any other words that expressed their feelings, but (perhaps unsurprisingly in view of the number of words offered) this option was not taken up.

angry appreciated auditioned bored calm capable
challenged clever cold comfortable confused devalued
developed educated embarrassed enlightened
examined explored fascinated frustrated grilled helped
hindered hot hungry informed insulted intelligent
interested interrogated intimidated lectured nervous
panicky probed put-down questioned relaxed ridiculed
scared scrutinised shown-up sleepy smug stressed
stretched stupid talked-down-to taught tense tested
thick thirsty tired tortured uncomfortable upset
valued weary worried

words presented to colearners

The second part of the feedback, asked specific questions to which the colearners were invited to use one-word or longer responses as they saw fit:

1. Did you find the tape recorder off-putting in any way?
2. Did you feel you learnt anything about science?
3. Did you feel you learnt anything about how well you understand your work?
4. Did you feel you were given the opportunity to explain your ideas during the tutorial?
5. Did you feel this tutorial was a worthwhile use of your time?
6. How did you feel about the duration of the tutorial?
7. How did you feel about the style of questioning?

Any other comments you wish to make?

Evaluation of any educational research programme should *ideally* be undertaken by someone in a position to understand the enquiry, *but independent of it* so that feedback may be collected and considered in a detached manner. In the present study this lone researcher personally handed a feedback form to his colearners and personally collected it back a minute or so later. The feedback collected should be considered with this limitation in mind.

§A10.2: The student feedback.

§A10.2.1: Physical environment.

Were the physical conditions such that colearners were able to concentrate on the task-in-hand?

Most of the interviews took place in a small teaching room, although some interviews took place in prep. rooms or labs.; often after day-classes finished at 5 p.m., but also at lunch times or during free periods. On 5 occasions (11%) colearners selected 'hot' from the word list - probably a reflection on the eccentric heating in the College ('cold' was not selected at all) and 'hungry' and 'thirsty' were each chosen three times (6.5%) - thirsty by the same student each time. 'Sleepy' and 'weary' were each selected twice (4%) and 'tired' (2%) once. These low incidents were reassuring - as was the selection of 'comfortable' (five times - 11%) and the non-selection of 'tortured'!

The use of a tape-recorder is often considered potentially distracting in interview work. In my own work I have found that colearners soon ignore it once good eye contact is established and discussion is underway. Perhaps this has been largely due to my colearners having volunteered to be interviewed on tape, and their relative maturity (age 16 plus.) The beginning of the first interview was used to collect personal data (name, age, previous qualifications, career plans) and then to listen back to check the recording - but also to allow colearners to become comfortable with the machine before the main part of the interview. In the feedback survey 41 responses claimed the recorder was not off-putting (89%) with 2 responses claiming it was off-putting (4%), and two responses that is was off-putting to a limited extent (4%), and one colearner did not respond to this question. (One of the colearners commented "Yes - it kept packing up" - an interview that I remember being rather frustrating as several batteries became discharged during the discussion. I later changed to a mains-powered recorder.)

§A10.2.2: Question style.

Did students find the questioning threatening?

The research interview can be very intense, and unlike the classroom question and answer session the teacher does not pass on to ask someone else if the interviewee shrugs her shoulders. The process of being questioned in depth for a period of thirty minutes to two hours is one that is often unfamiliar. My colearners were 'free to leave at any time', as they were 'just helping me with my enquiry', but it was important to know how they felt about such an interrogation?

Colearners commonly felt 'questioned' (selected 23 times, 50%), 'tested' (22, 48%) and 'examined' (18, 39%). Sometimes they felt 'probed' (9, 20%) - but 'interrogated' and 'grilled' were each only selected once (2%) 'Nervous' was selected 4 times (9%), 'panicky' 3 times (6.5%), 'worried' twice (4%) and 'tense' once (2%). However 'relaxed' was chosen 5 times (11%) and 'calm' 4 times (9%).

Although the interviews were sometimes longer than a lesson they did not seem to drag for the colearners ("I felt tested, it was a sort of challenge"). No one selected 'bored' and comments included "I didn't really take note of the time as I was busy in the question" and "it went quickly".

§A10.2.3: The value of the experience.

Did the students find the experience worthwhile?

There was unanimity in responding that the sessions had been a worthwhile use of time (i.e. 46, 100%) Most thought they had learnt something about science (31, 67%): the words 'educated' and 'taught' were each selected from the words list 14 times (30%), and 'informed' was selected 9 times (20%). 'Helped' was one of the most popular words selected (23 selections, 50%.)

On only one occasion (2%) did the respondent report not learning anything about how well the work was understood (there were 44 responses {96%} that learning did take place and there was one non-response to this question) and there were 45 responses that opportunity was given to colearners to explain their ideas (98% - one non-response to this question): comments included "ample", "plenty", "definitely!" and "...I was given sufficient time to answer questions."

The colearners generally seemed to have the metacognitive awareness to benefit from the experience as an opportunity for self-evaluation, as the following comments show:

> "I know less than I thought"
> "...I feel that I need to know more"
> "...it made me think more about certain issues"
> "...it seems that I know the facts but don't know why they are facts", "...I know things happen but I don't know why"
> "...I don't know as much about bonding as I thought"
> "sometimes I felt I didn't really know what I was talking about"

and

> "lacking ability to apply to simple situations."

The unfamiliar style of questioning led to a number of responses, some positive,

> "I felt that the time to answer the question was good. I didn't feel under pressure to answer straight away."
> "Very clear + easy to understand"

> "It was variable - I liked that"
>
> "Good. It made sure I wasn't guessing."
>
> "Well structured"

but not all the feedback was positive,

> "It was clear but repetitive which makes it seem as though my answers were wrong"
>
> "It was all right, maybe a bit off-putting at times"
>
> "A little confusing at times"

and for one response it was not clear whether the colearner intended the comment as positive, negative or just an observation:

> "I had to think quite a lot about some questions before answering."

Did the students feel they learnt through the process of being interviewed?

The most popular selection from the word list was 'challenged' (38 selections, 83%) with 'developed' being another popular choice (22 selections, 48%), and a word that also appeared in the comments, "...made me develop my ideas further." The researcher may recognise the importance of talking ideas through as part of the learning process, and accept that sometimes this will be a difficult experience for the person exposing the limits of their understanding to an audience. Students might not be expected to have the same overview of the process, and whilst some felt 'clever' (5 selections, 11%), 'intelligent' (5, 11%), 'enlightened' (3, 6.5%) or 'capable' (2, 4%), other feelings experienced on a few occasions were 'frustrated' (3, 6.5%), 'embarrassed' (2, 4%), 'shown-up' (2, 4%), 'thick' (2, 4%) and 'talked-down-to' (1, 2%). (No colearner reported feeling 'insulted', 'put-down', 'ridiculed' or 'stupid'.)

Perhaps of some concern was that colearners were not just challenged but often 'confused' (15 selections, 33%). The researcher might justify confusion as necessary if certain models of conceptual change are being used (e.g. "There must be dissatisfaction with existing conceptions. Scientists and students are unlikely to make major conceptual changes until they believe that less radical changes will not work", Strike & Posner, 1985), or in terms of Vygotsky's zone of proximal development (see chapter 2). However, what is acceptable from the researcher's viewpoint could still be a distressing experience for the colearner. In the present work, although the descriptor 'confused' was selected quite a lot, only a few of the open-ended responses referred to this aspect, one respondent commented that the style of questioning was "a little confusing at times." Another commented "I think that I understand most of my work - but I confuse things a little." Indeed confusion did not seem to spoil the experience, "sometimes I felt confused, but it was interesting." 'Interested' was one of the most common words selected (22 selections, 48% - 'fascinated' was also chosen twice (4%)) and some colearners seemed to find the level of attention flattering: 'appreciated' was selected 7 times

(15%) and 'valued' thrice (6.5%.)

Colearners' recognition that they were developing their ideas through the conversations was most encouraging. One of the colearners reported that

> "...I learnt things that I know and those that I don't. I realised that I know some things that I didn't know I knew"

and another comment was

> "I did put to use some basic facts, and use them to work out harder examples".

Other responses were that "it helped me think more deeply about first principles", that it "cleared up loose ends" and that "I was reminded there is more than one way of looking at a situation."

§A10.3: Tajinder's feelings about his experience of the research.

Colearner Tajinder asked if the interview sessions could be a regular event as he found them particularly useful. Over the period of his course 23 tape recorded interviews were undertaken. Tajinder soon become somewhat bored with the format of the feedback forms. I suggested that we could do without them if some alternative record of his reaction was made. He agreed to keep a brief diary of his feelings about the interviews instead, and passed this to me at the end of the course. Some of his comments may be used to support the points made above from the more structured feedback. He included points relating to how well he understood the work,

> "Worked out that I was wrong to think that all valent electrons took place in bonding, but worked it out in the end.
>
> "Most frustrating lesson [sic]. I was too unsure on many things, even things that I had sorted out last year."
>
> "I learned a lot about molecular orbitals today."
>
> "Didn't do to well today, I couldn't think properly."

Tajinder showed an awareness of how his thinking develops through the discussions,

> "Very helpful made me think about the law, and it came back to bonding, which I enjoy actually. Made me think a lot today."
>
> "I had learned about this last year, and understood the principle involved, but today was able to 'spit it out' as it were, and put it into words."
>
> "Made me think about atoms and how they are made up."

Tajinder sometimes expressed a sense of enjoying the dialogue, as well as finding the sessions worthwhile,

> "I liked the lesson today."
>
> "I enjoyed the tutorial today."
>
> "The session today was quite good, I found it interesting and very helpful."
>
> "The tutorials [sic] are helping me revise no end..."

Tajinder, like the other colearners, recognised that the sessions were lengthy and challenging, and found the constant questioning an 'intense' experience,

> "Long sessions, about 2 hr. 15 min., but it went very quickly. Very difficult lesson [sic]."
>
> "Very long, but worthwhile session."
>
> "I find these sessions quite intense, very hard work, they rack my brains and I find out just how well I really do know my work."
>
> "Today was a very long session, but time went very quickly."

Sometimes, when he didn't seem to be making progress he felt frustrated and time seemed to drag. At these times he did not feel was learning anything, but this frustration passed,

> "Bit slow to start off, and found this a bit frustrating. Today was quite an enjoyable tutorial [sic] after the first 20 minutes."
>
> "It started off bit slow, and a bit frustrating but it was okay after that."
>
> "Sometimes I wonder whether I am learning anything during the tutorial[sic] but I realise I learn more in the tutorialbecause I am made to think how well I think I understand the work. Therefore if a problem is set to me I can hopefully think my way around it and not just get stuck."

With a student wishing to commit so much time to the research it became even more important that the interviews should be based around a shared agenda. One aspect of this was that Tajinder fed in particular topics that he wished to discuss, so that the actual interview agendas were negotiated between us. I was able to do this as my focal topic (chemical bonding) was fundamental enough to the course that I was confident that most discussions would produce data relevant to my own research questions, and indeed the variation of contexts was useful.

Tajinder did not enjoy undertaking Kelly's construct repertory test as much as the interviews,

> "I do not like the picture cards very much and find it difficult to find categories. It is helpful and makes me think. It was a difficult lesson today."

so I undertook this task less with Tajinder then I would ideally have done,

> "First tutorial with picture cards for a long time. Today's tutorialwas not very interesting. I do not like it very much. I can't explain it, but it

> is very frustrating. Difficult lesson."

I also varied the way I approached the task in an attempt to make it more fruitful for him:

> "Picture cards. The session was okay and it cleared up my theories of bonding. Pretty useful."
>
> "Picture cards. More useful than normal picture cards. Learned a lot as usual, and is going fine. The tutorials are becoming more and intense and longer but it's all worth it in the end."

Appendix 11.

Examples of intra-interview validation.

§A11.0: Checking the interviewer's interpretations.

One of the major advantages of interview techniques is the flexibility it provides the interviewer to interact with the respondent. By using in-depth interviews as the main research technique there is scope for considerable 'internal validation' of the interviewer's interpretations of the colearners comments during a single interview.

In chapter 4 (§4.10.1) it was pointed out that *within* an interview the reliability of the researcher's interpretation of a colearner's comment may be checked in a number of ways.

1) confirming responses by repeating or rephrasing questions (§A11.1);
2) clarifying ideas by asking follow-up questions (§A11.2);
3) paraphrasing what one believes to be the colearner's argument, and seeking confirmation (§A11.3);
4) returning to the same point in the same context later in the interview, to see if a consistent response is given by the colearner (§A11.4);
5) approaching the same point through a different context later in the interview, to see if the colearner gives a consistent response in the different contexts (§A11.5).

A§11.1: Confirming responses by repeating or rephrasing questions.

e.g. 1 - confirming that Annie did not class interatomic binding as a form of bonding:

A1
17 I: What I would like to know: is there any bonding going on there?
19 A: Erm. No.
...
48 I: Er, so we've got a nucleus, and we've got electrons, and they are being held in, and you wouldn't identify any kind of bonding in that diagram?
49 A: No.
50 I: No. So there's no, no chemical bonds there?
51 A: No.

e.g. 2 - confirming that Annie did not consider a diagram of a K^+ - F^- ion pair to exhibit bonding:

A1
349 I: So in that diagram, have we got any kind of chemical bond?
350 A: No.
351 I: Did we have a chemical bond in the previous two diagrams, the lithium iodide, and the hydrogen?
352 A: Yeah.
353 I: Yeah. But there is no chemical bond here?
354 A: No,
I: okay,
A: because they're not combined.

§A11.2: Clarifying ideas by asking follow-up questions:

e.g. 3 - clarifying whether Annie was suggesting all electrons shown in a tetrachloromethane molecule were moving around, or just some:

A1
197 I: Do you think the electrons actually stay in one place here? Or do you think they move around?
198 A: No, I think they move around.
199 I: All electrons?
200 A: No I think the ones that are fixed to the carbon would stay,
I: so you're pointing at
A: more or less.
201 I: You are pointing to these ones involved,
A: yeah,
I: in the bonding?
202 A: Yeah, the ones that are involved in that, they can't really move around, like all the way around the shell.
203 I So these ones would be able to,
A: yeah,
I: but these ones would be fairly fixed, because of the bonding.
204 A: Yeah.

e.g. 4 - clarifying what Annie understood by the term 'electron rich':

A1
461 I: Now do you know what compound that is? Any idea?
•••
462 A: Looks like a benzene ring.
463 I: Yeah, that's right. Any idea what this, er, strange looking circle in the middle is?
A: > It's... >
I: < Or < what it's meant to represent?
464 A: Shows where the electrons are, because it's electron rich.
...
475 I: Okay, so why do you say it's electron rich, what does that mean exactly?
476 A: Erm, not really sure, but I wrote it down yesterday. {Both laugh.}

§A11.3: Paraphrasing what one believes to be the colearner's argument, and seeking confirmation.

e.g. 5 - paraphrasing Annie's comments about the meaning of 'plus' and 'minus' symbols:

A1
280 I: So the plus means one electron more than an outer, the full shell,
A: yeah
I: and the minus means one electron
A: minus
I: less than an outer shell,
A: yeah,
I: and that's what holds them together?
281 A: Yeah.

e.g. 6 - paraphrasing Annie's comments about the forces between lithium and iodine in a molecule of lithium iodide:

A1
321 A: It's the same sort of thing again - the lithium combines with the iodine - to make a stable outer shell between the two, by sharing electrons,
I: uh hm,
A: but the lithium has a smaller charge, or smaller pull than the iodine, so the actual shape of it goes in towards. It sort of goes inwards because its attracting the lithium, whereas if the lithium was attracting it, it would be like a reverse picture.
322 I: So, so the iodine's attracting what, sorry?
323 A: The lithium.
324 I: The iodine's attracting the lithium, and the lithium is not attracting the iodine?
325 A: Yeah, they're both attracting each other but because this one's got a larger force,
I: uh huh,
A: then it will pull to.., towards the lithium more.
327 I: The iodine's got a larger force,
A: yeah,
I: so it will pull towards the lithium more?
328 A: Yeah.

e.g. 7 - paraphrasing Annie's ideas about how successful counter ions with different valencies are in forming compounds:

A1

400 A: Yeah, they're sort of attracting there [indicating on diagram], they're sort of like matched up, elements which they have been chosen to join with.

401 I: Uh hm.

402 A: But none of them have actually reached that far. And it seems like aluminium is being more successful, than the potassium.

403 I: Yeah, why do you say that, yeah?

404 A: Because the cone, cone shape on it, sort of goes further over, to all but reach it, whereas the potassium one sort of like stops quite a bit shorter.

405 I: That's true, yes, it's certainly drawn that way, isn't it. The aluminium one is nearly getting there, and the potassium's not making much

A: no

I: headway really. Any ideas why that might be?

• • • • • • • • • • •

406 A: Is it something to do with the charges, sort of aluminium's got three plus charge, so if it did combine, then it would still have one electron over, but it would complete the outer shell. But potassium would still leave it with one electron less. So the pull isn't so great.

407 I: Right, so the potassium could only provide it with one electron, and it needs two,

A: yeah,

I: is that what you're saying? Aluminium could provide it with three and it only needs two,

A: yeah,

I: so that's going to be more successful. Okay, if I had one in the middle here then which I haven't got, let's say I had calcium,

A: hm,

I: which would be two plus,

A: yeah,

that could provide two electrons.

408 A: Yeah.

409 I: So do you think that would be somewhere in between these two diagrams, or because it can provide the right number of electrons do you think it would be more successful than the aluminium?

410 A: Yeah, the shape would be like the bottom one of the two, but the calcium circle would actually be inside sort of the nose, the cone.

411 I: So, they'd actually coalesce?

412 A: Yeah.

§A11.4: Returning to the same point in the same context later in the interview, to see if a consistent response is given by the co-learner.

e.g. 8 - checking to see if Annie genuinely classed bonds in benzene as ionic, or had become confused:

A1

447 I: Well what about picture twelve then? Can we see any bonds there?

448 A: Yes.

449 I: Right, what kinds of bonds have we got there do you think?

• • •

450 A: Ionic.

451 I: These are ionic bonds. How many bonds do you think are in there?

• • • • • • • • •

452 A: Twelve.

453 I: Twelve, okay. Are all the bonds the same?

454 A: Well they're sort of two types.

455 I: Uh hm.

456 A: There's C to H bonds or C to C bonds.

457 I: Right, do you think they're both ionic bonds, both those types?

458 A: Yeah.

then later:

499 I: What about in the previous diagram, when we looked at number twelve: You said what, there were twelve ionic bonds there?

500 A: Mm.

501 I: Any covalent bonds?

502 A: I've got it the wrong way round. Should have been covalent bonds, not ionic.

e.g. 9 - confirming that Annie had learnt to distinguish between the sodium atom and the Na^+ species:

A2
42 I: you've told me what you think the electronic configuration of
A: yeah
I: sodium is, which I think is 2.8.1 you said, yeah?
A: Uh hm, yeah
I: chlorine 2.8.7, this, this here, this Na^+,
A: yes
I: can you tell me what the electronic configuration you think of that is, Na^+?
43 A: Erm, 2.8
44 I: 2.8. What about the chlorine, sorry this Cl^-?
45 A: 2.8.8.
46 I: 2.8.8. So they're different to the actual atoms?
47 A: Yes.

and later

A2
179 I: Can we just focus back to, this one, sodium chloride?
180 A: Yeah.
181 I: What did you tell me was the electronic configuration of the sodium atom?
182 A: 2.8.1
183 I: What about the sodium ion shown there?
184 A: It's 2.8
185 I: What about the chlorine atom?
186 A: It's 2.8.7
187 I: And what about the chloride ion?
188 A: It's 2.8.8

§A11.5: Approaching the same point through a different context later in the interview, to see if the co-learner gives a consistent response in the different contexts.

e.g. 10 - finding if Annie's ideas about the degree of localisation of bonding and non-bonding electrons in the aluminium chloride dimer were consistent with her ideas about tetrachloromethane:

A1
197 I: Do you think the electrons actually stay in one place here? Or do you think they move around?
198 A: No, I think they move around.
199 I: All electrons?
200 A: No I think the ones that are fixed to the carbon would stay,
I: so you're pointing at
A: more or less.
201 I: You are pointing to these ones involved,
A: yeah,
I: in the bonding?
202 A: Yeah, the ones that are involved in that, they can't really move around, like all the way around the shell.
203 I So these ones would be able to,
A: yeah,
I: but these ones would be fairly fixed, because of the bonding.
204 A: Yeah.

and later

A1
593 I: Right, can any of those electrons move around?
594 A: Yes.
595 I: Which ones?
596 A: The ones in the chlorine. 'Cause the aluminium ones are sort of fixed to the chlorine bonds that they're sharing.
597 I: Right, so these six here, these belong to the chlorine?
598 Yeah.
599 I: And they can move around?
600 A: Yeah.
601 I: But the eight in the central circles, they all belong to the aluminium?
602 A: Yeah.
603 I: And they can't move?
604 A: Yeah, they're more stable, more fixed.

e.g. 11 - to find if Annie's interpretation of the '+' symbol in Na^+ was also applied in K^+ and Al^{3+}:

A1

260 A: The attraction from the plus to the minus because like chlorine's minus an electron and sodium is over an electron. So they could just like hold them together, but not actually combine.

261 I: Right, chlorine's, so sodium's, say that about the electrons again.

262 A: Sodium has like one extra electron, 'cause it has like an extra electron in its outer shell,

I: uh huh,

A: and chlorine has seven electrons in its outer shell so its minus an electron so by sort of exchanging,

I: huh hm,

A: the sodium combining with the chlorine just by force pulls they would hold together.

and later

333 I: Right, okay, so this one here where it's got a K and a plus, what does that represent?

334 A: Potassium.

335 I: Right, is that,

A: That's just a,

I: a potassium molecule, or?

336 A: An atom that has an extra electron.

337 I: Potassium atom, and it's got one extra electron over a full shell

A: yeah

I: and that's what the plus means, one more electron than it wants?

338 A: Yeah.

and later still

361 I: So just look at potassium, that's K^+ again, isn't it?

362 A: Yeah.

363 I: So, you've told me that the plus means?

364 A: One electron in the outer shell, that's over.

365 I: Over what it would like to have?

366 A: Yeah, yeah.

367 I: What about this aluminium three plus? Al^{3+}? What do you think about that?

368 A: That has three electrons in its outer shell more than it needs, three over.

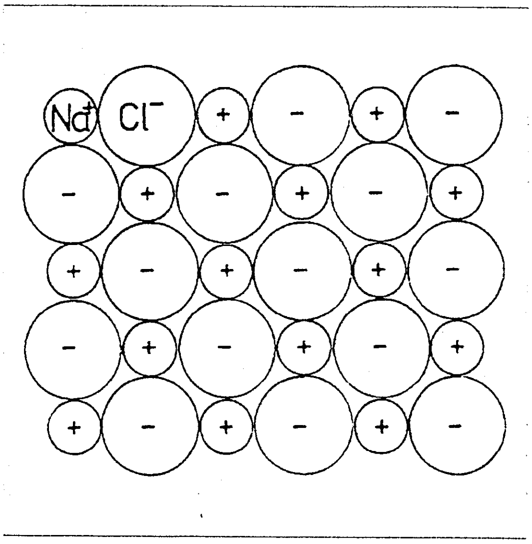
Appendix 12.

Focal diagrams prepared for the interviews.

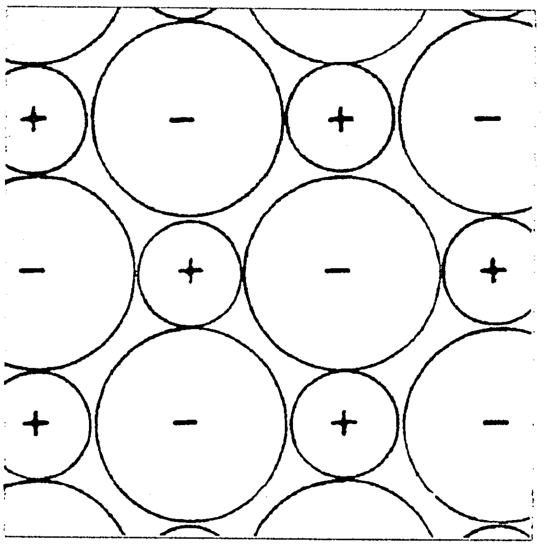
As described in chapter 5 (§5.1.2) diagrams were produced to act as foci in the interviews. These figures are reproduced here. (The diagrams were scanned into my computer using an *Apple OneScanner 600/27*, and processed with the *OneScanner Dispatcher* software.)

The first figure, over, shows a reproduction of the image from focal figure 1, as it originally appeared on A4 paper. The other diagrams have been reproduced as *reduced size* images. To show the detail of the diagrams these images have been cropped (excluding much of the blank margins): all the original diagrams included the figure number in the corner, as in the example over. As the original images covered different extents of the A4 sheets, the extent of reduction is given in parenthesis.

For example, focal figure 5 has been reproduced at 50% of its original linear dimensions: for comparison the reduced figure is juxtaposed against a detail at the original scale:

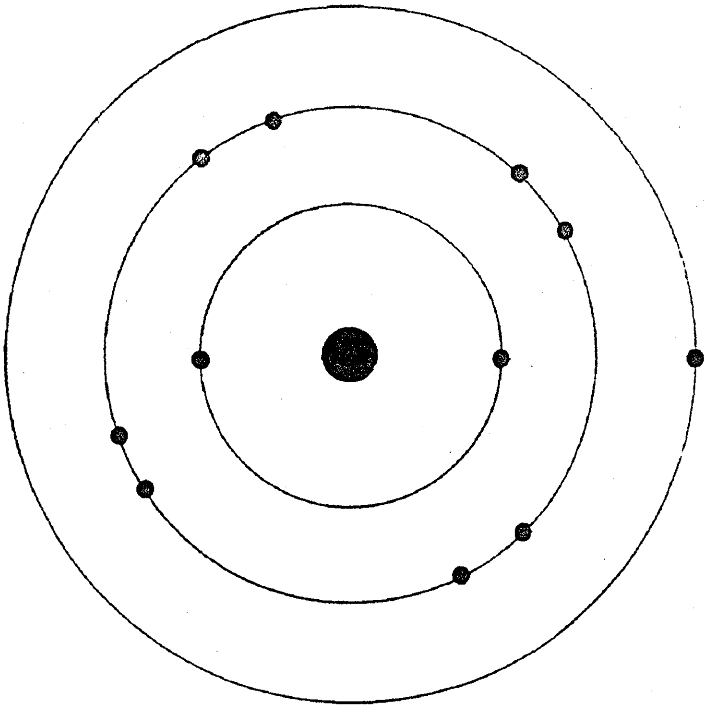


focal figure 5 (50%)

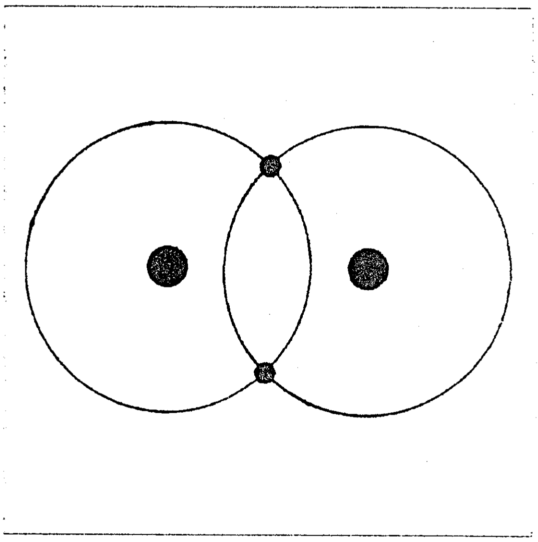


focal figure 5 (detail)

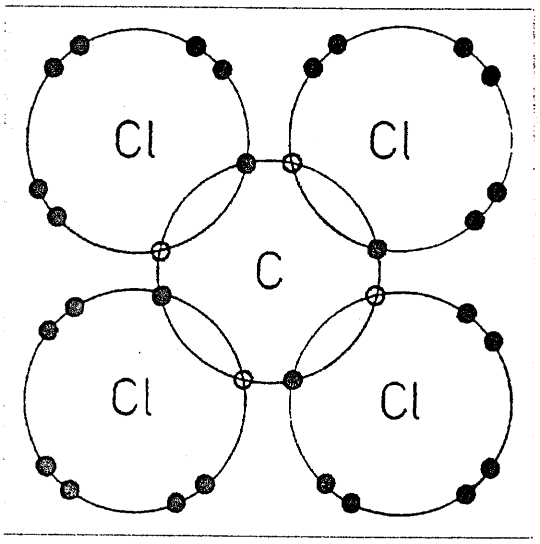
1



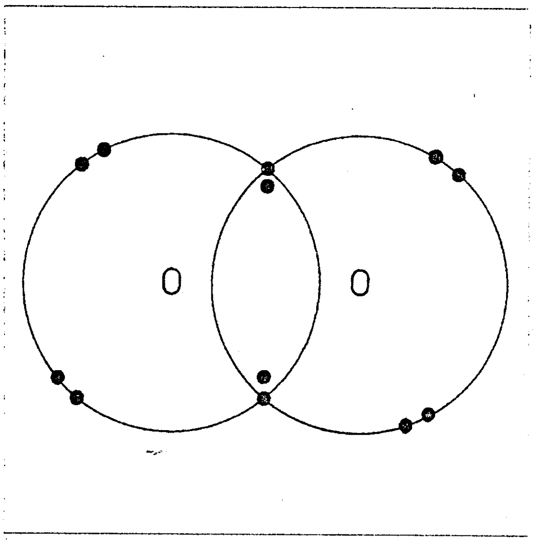
focal figure 1 (original size)



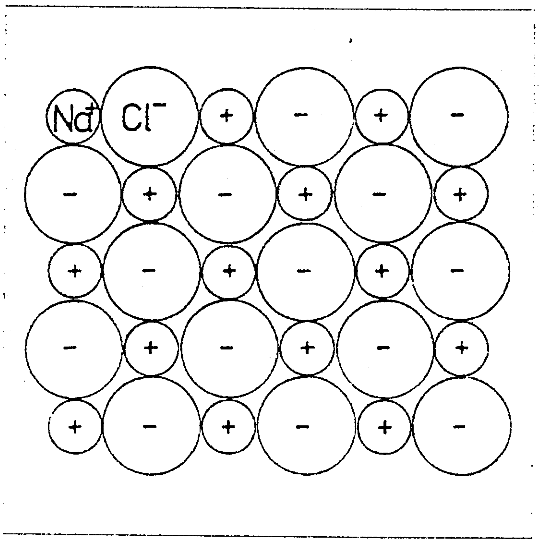
focal figure 2 (75%)



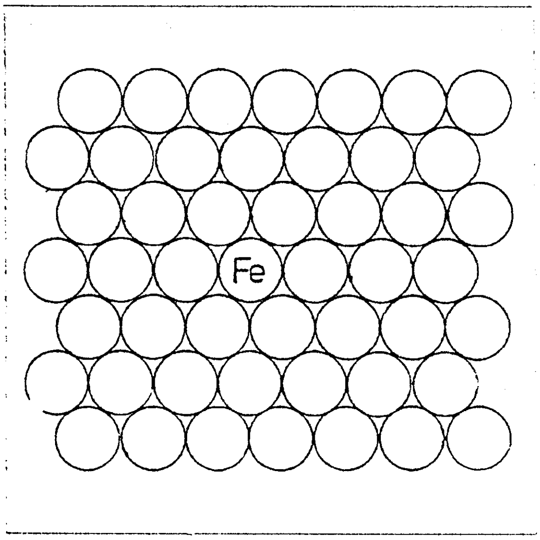
focal figure 3 (71%)



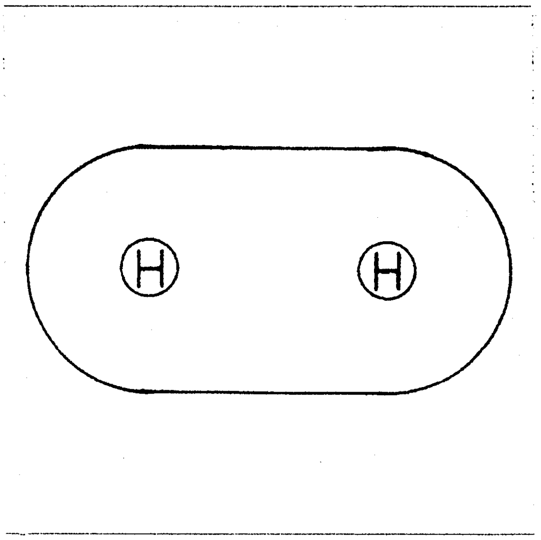
focal figure 4 (35%)



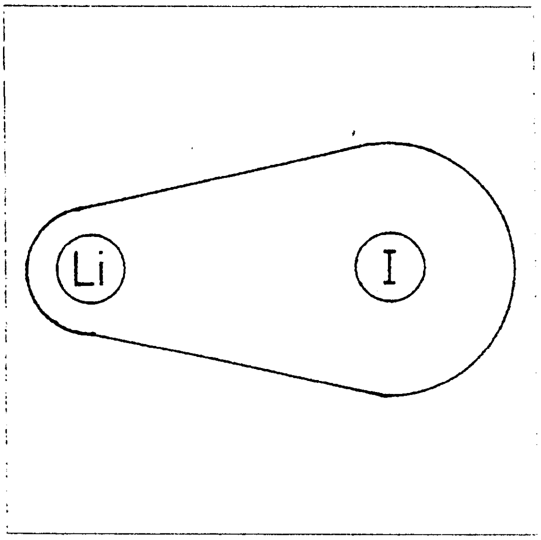
focal figure 5 (50%)



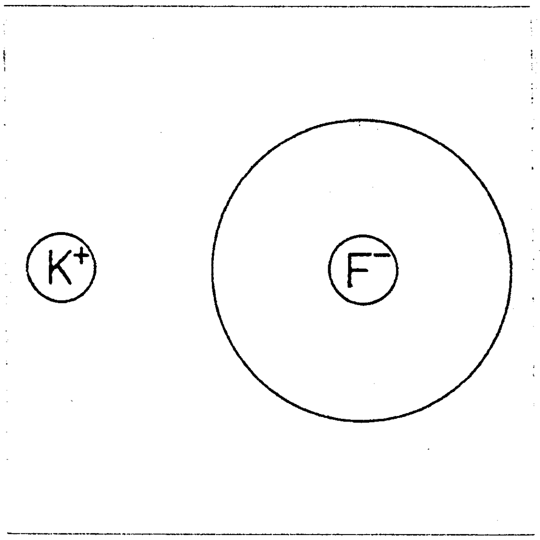
focal figure 6 (48%)



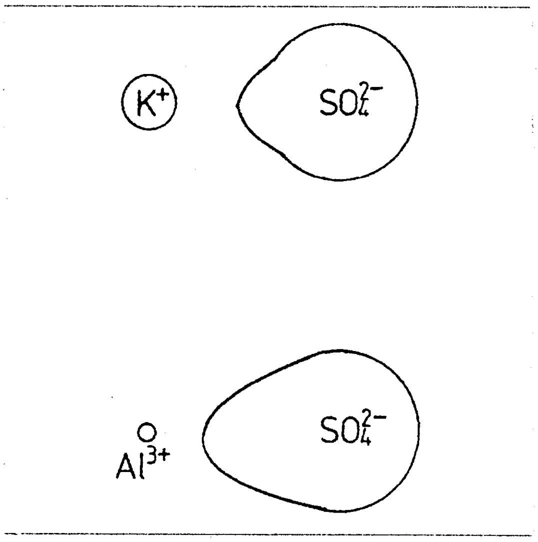
focal figure 7 (50%)



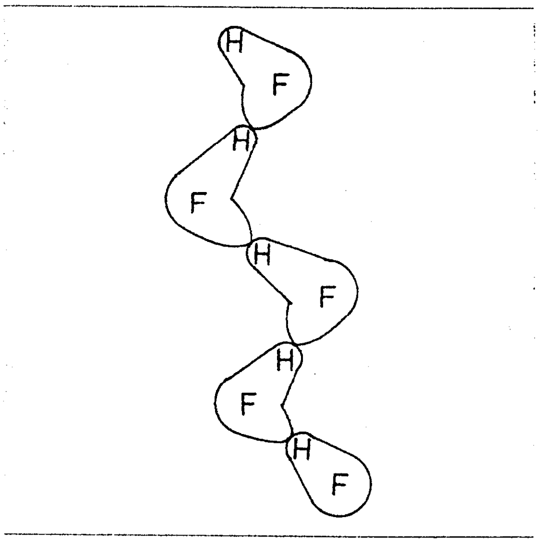
focal figure 8 (64%)



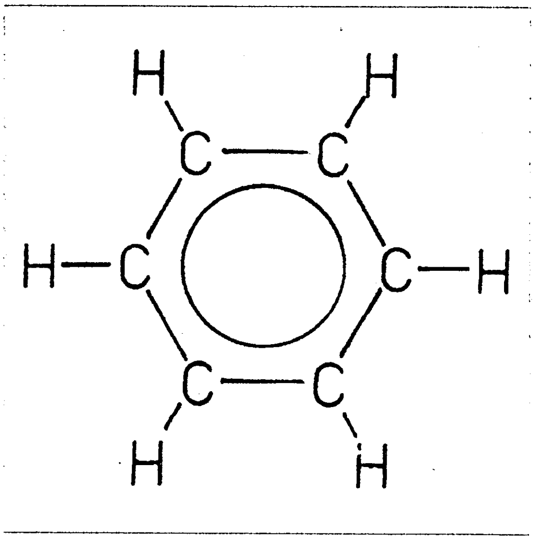
focal figure 9 (45%)



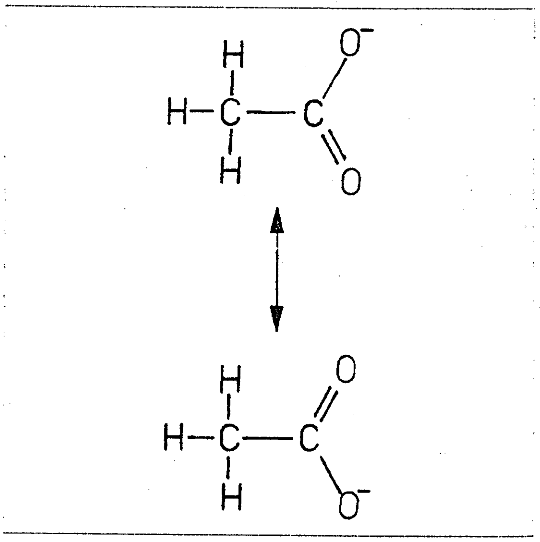
focal figure 10 (34%)



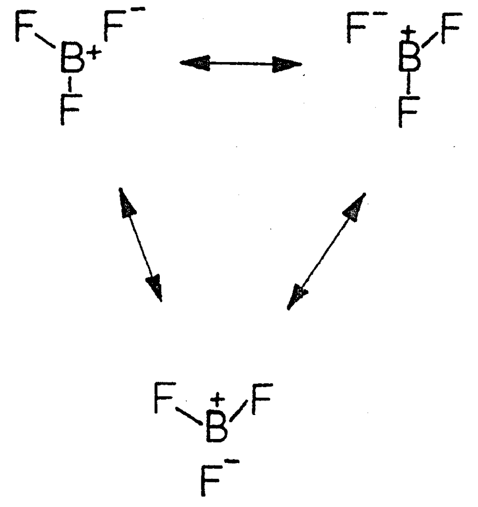
focal figure 11 (28%)



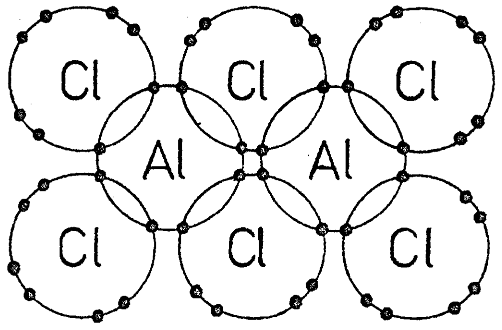
focal figure 12 (59%)



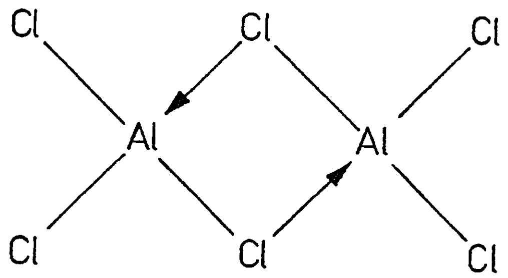
focal figure 13 (36%)



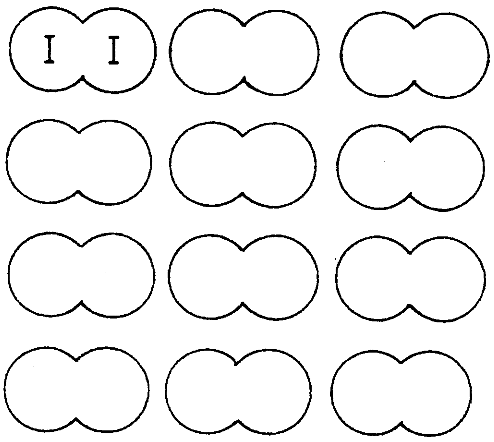
focal figure 14 (41%)



focal figure 15 (53%)



focal figure 16 (37%)



focal figure 17 (37%)

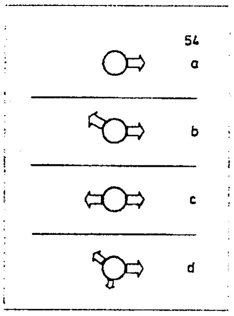
The figures were intended to provide opportunities to talk about aspects of chemistry that had been identified as significant: atomic binding (focal figure 1), covalent bonding (2, 4, 7, 17), ionic bonding (5, 9), metallic bonding (6), polar bonding (3, 8, 10, 11, 14, 15, 16), multiple bonding (4, 12, 13), hydrogen bonding (11), dative bonding (15, 16), van der Waals' forces (17) and resonance (12, 13, 14).

Appendix 13.

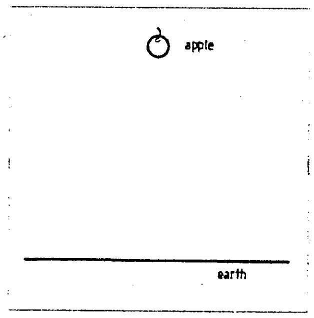
Focal figures relating to force and energy.

The following figures were added to the original deck of 17 chemistry-related diagrams to act as foci for discussion of ideas of forces and electrostatics underlying the topic of chemical bonding (see chapter 5, §5.1.2).

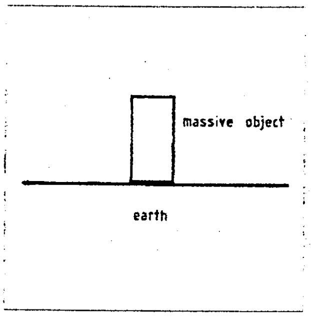
All the original figures were drawn on A4 sheets. The reproductions are all reduced (see appendix 12), and the figures in parentheses give the linear dimensions of the reduced reproduction as a percentage of the original figure.



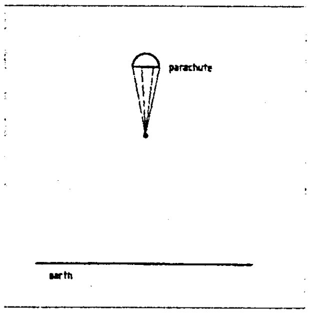
focal figure 54 (13%)



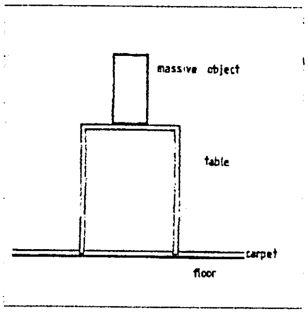
focal figure 55 (25%)



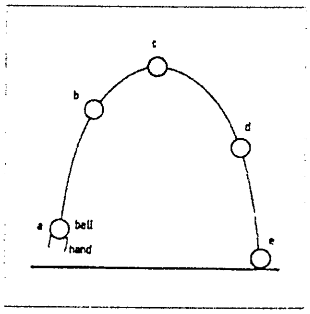
focal figure 56 (27%)



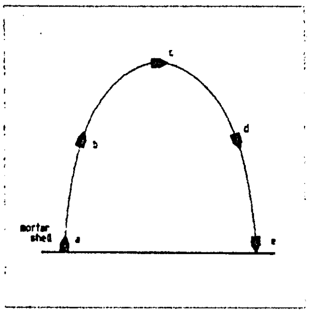
focal figure 57 (19%)



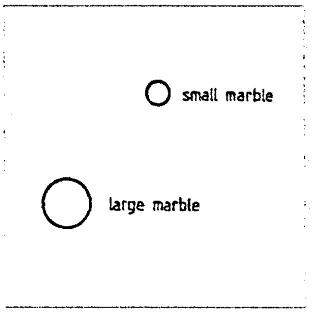
focal figure 58 (22%)



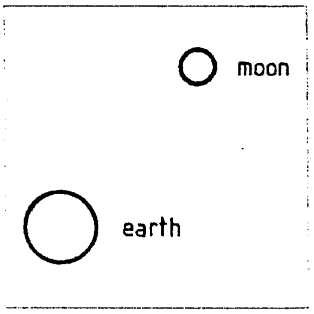
focal figure 59 (22%)



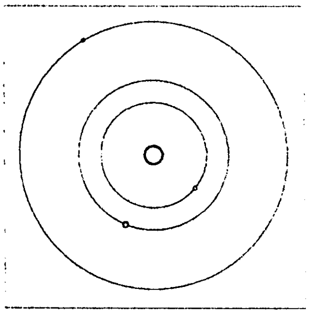
focal figure 60 (20%)



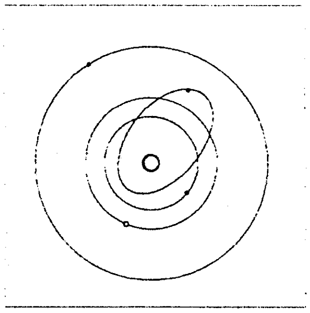
focal figure 61 (33%)



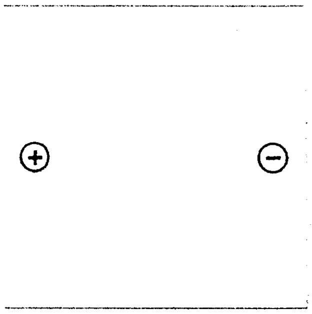
focal figure 62 (48%)



focal figure 63 (25%)



focal figure 64 (22%)



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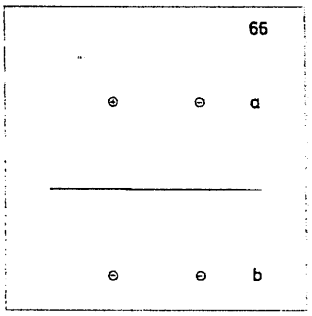
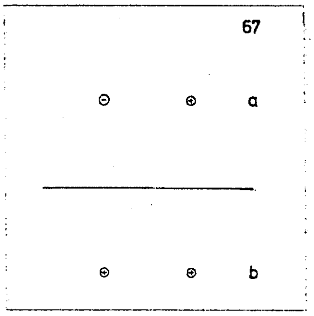


focal figure 66 (16%)



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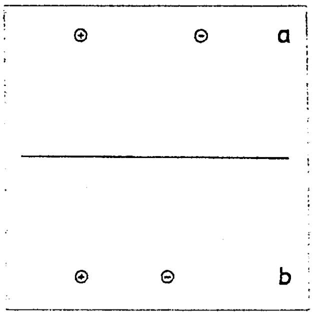
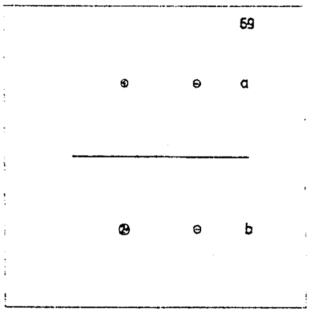
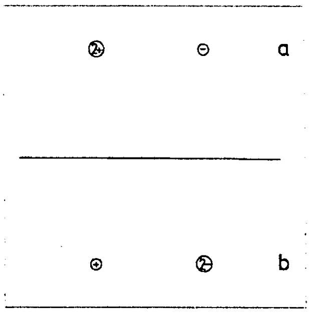


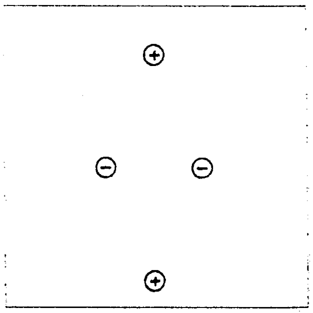
focal figure 68 (23%)



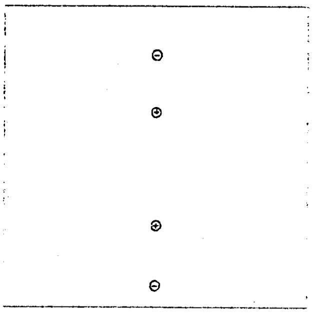
focal figure 69 (14%)



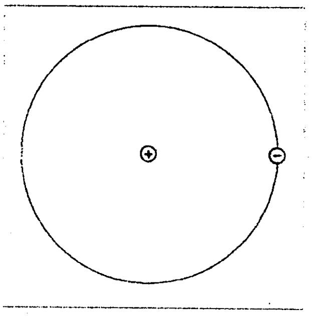
focal figure 70 (20%)



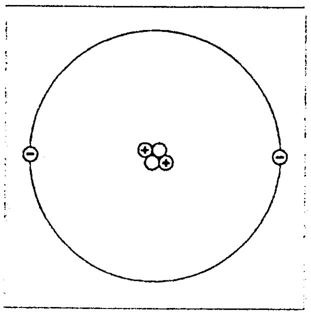
focal figure 71 (37%)



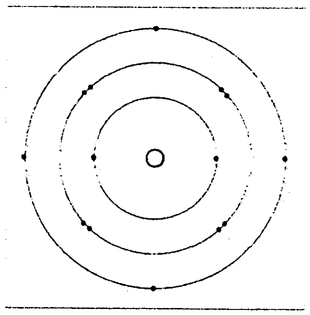
focal figure 72 (18%)



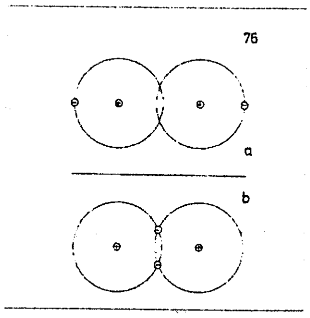
focal figure 73 (29%)



focal figure 74 (27%)



focal figure 75 (23%)



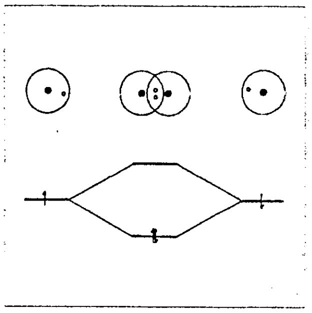
focal figure 76 (13%)

Appendix 14.

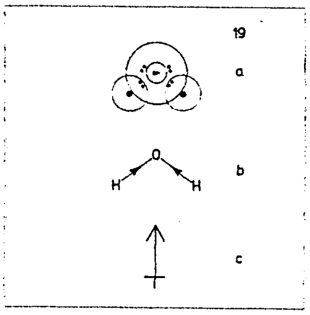
Additional focal figures added during the interviewing of the first cohort of colearners.

The following figures were added to the original deck of 17 chemistry-related diagrams (reproduced in appendix 12) to provide additonal contexts for discussing aspects of chemical bonding (see chapter 5, §5.1.2).

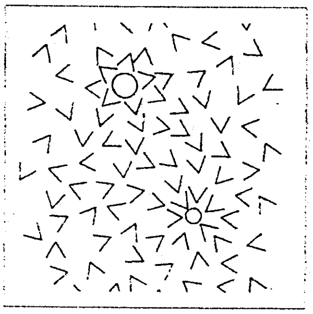
All the original figures were drawn on A4 sheets. The reproductions are all reduced (see appendix 12), and the figures in parentheses give the linear dimensions of the reduced reproduction as a percentage of the original figure.



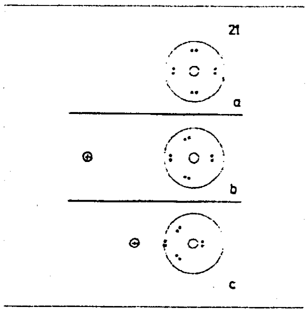
focal figure 18 (19%)



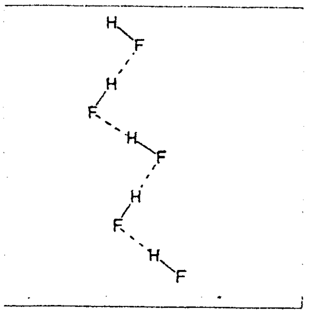
focal figure 19 (13%)



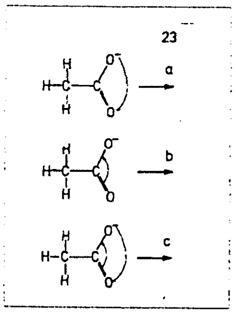
focal figure 20 (17%)



focal figure 21 (13%)



focal figure 22 (16%)



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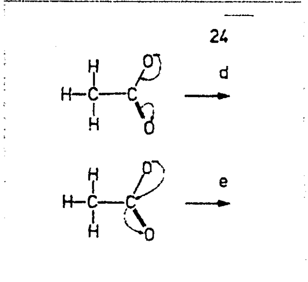
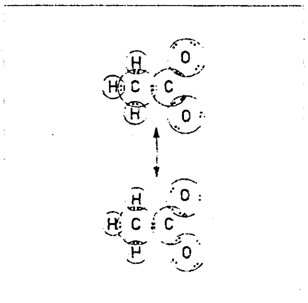
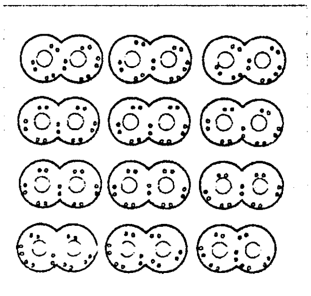


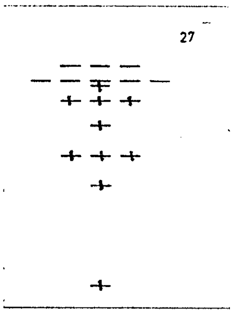
focal figure 24 (17%)



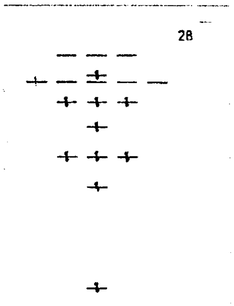
focal figure 25 (15%)



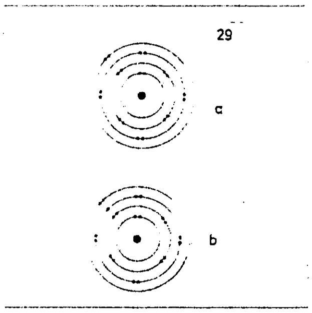
focal figure 26 (20%)



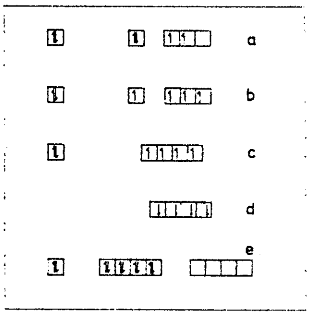
focal figure 27 (13%)



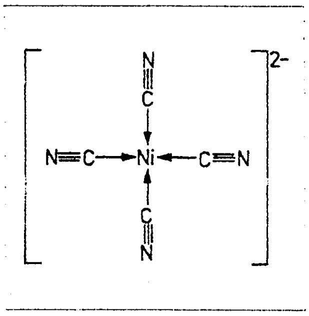
focal figure 28 (13%)



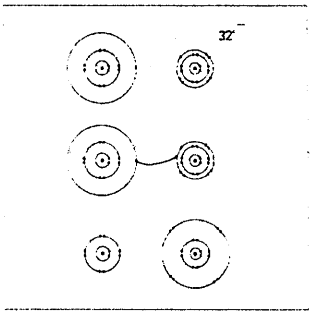
focal figure 29 (13%)



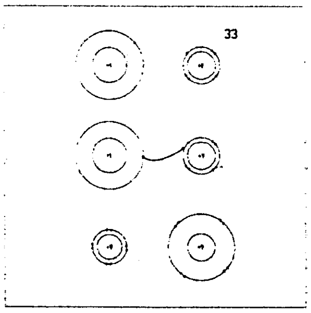
focal figure 30 (15%)



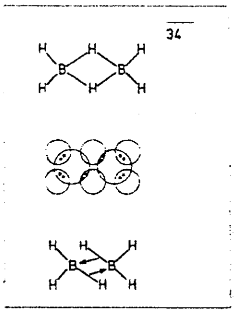
focal figure 31 (20%)



focal figure 32 (12%)



focal figure 33 (12%)



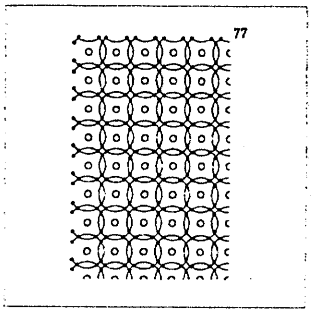
focal figure 34 (13%)

Appendix 15.

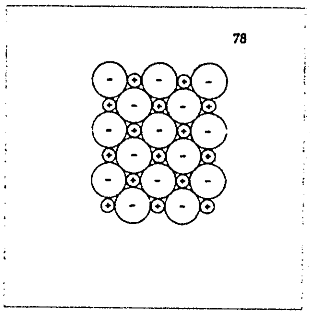
Additional focal figures added during the interviewing of the second cohort of colearners.

The following figures were added to the original deck of 17 chemistry-related diagrams (reproduced in appendix 12) to provide additonal contexts for discussing aspects of chemical bonding (see chapter 5, §5.1.2).

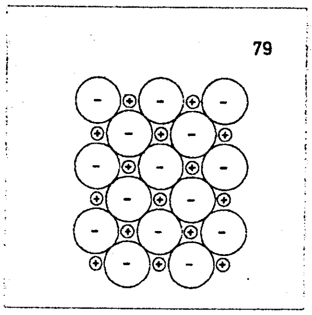
All the original figures were drawn on A4 sheets. The reproductions are all reduced (see appendix 12), and the figures in parentheses give the linear dimensions of the reduced reproduction as a percentage of the original figure.



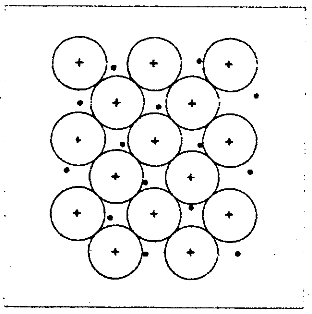
focal figure 77 (13%)



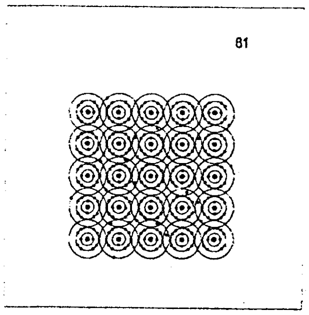
focal figure 78 (13%)



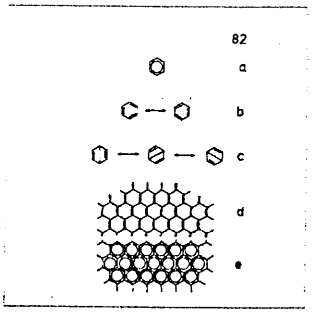
focal figure 79 (17%)



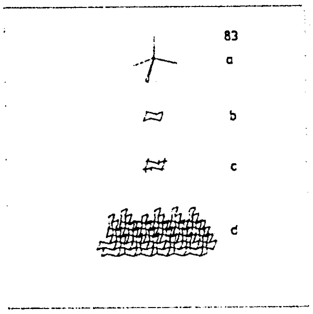
focal figure 80 (20%)



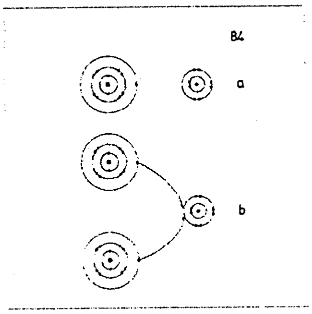
focal figure 81 (14%)



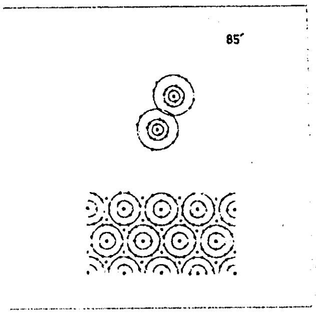
focal figure 82 (13%)



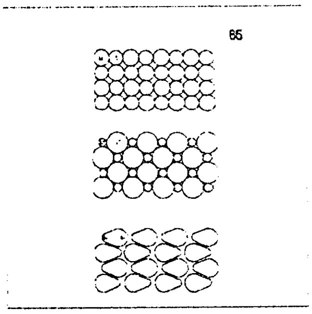
focal figure 83 (12%)



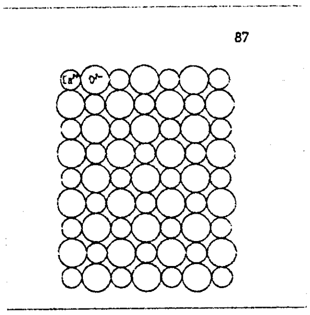
focal figure 84 (13%)



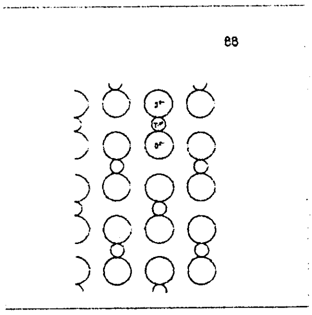
focal figure 85 (12%)



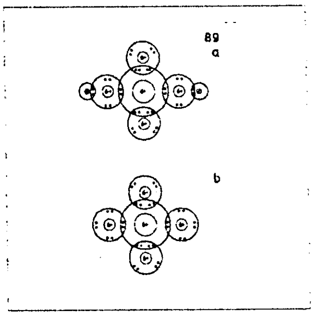
focal figure 86 (13%)



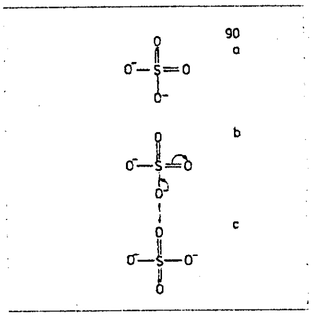
focal figure 87 (14%)



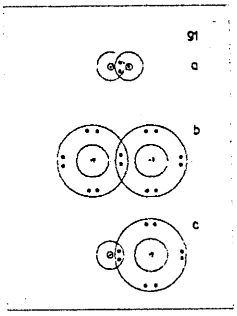
focal figure 88 (13%)



focal figure 89 (12%)



focal figure 90 (13%)



focal figure 91 (12%)

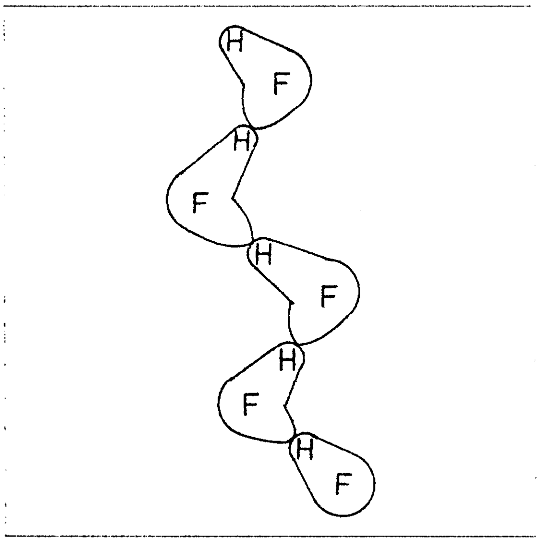
Appendix 16.

Examples of theoretical sampling: supplementing the deck of focal diagrams as a response to data collected.

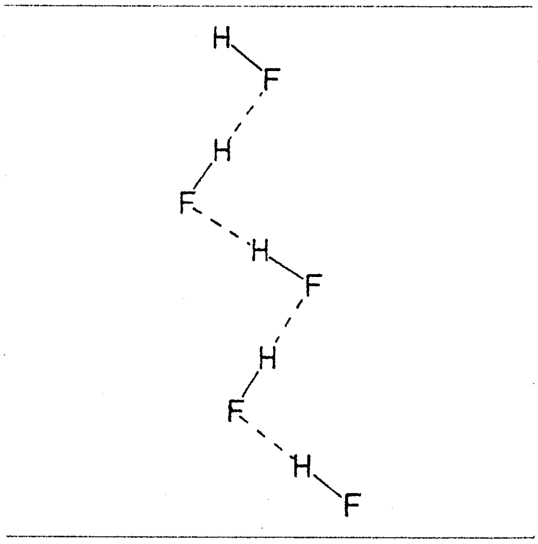
As explained in chapter 5 (§5.1.2) 17 focal figures were prepared in advance of data collection commencing (see appendix 12), but further figures were produced as the research progressed. As a result of considering the data collected additional foci were generated both to explore colearners' notions of prerequisite physics concepts (appendix 13), and to provide alternative figures of chemical species (appendices 14 and 15).

The additional diagrams of chemical structures were designed to complement the initial 17. In this appendix some insight will be provided into how the ideas being elicited from colearners were used to direct lines of questioning in subsequent interviews (*theoretical sampling*, see chapter 4, §4.4.1). The additional diagrams were generated to provide additional foci to facilitate the exploration of these emerging themes in the research.

So, for example, as focal figure 11 was not always perceived as representing bonding ***between*** HF molecules. This could have been a reflection of learners' categorisation of bonding, or a specific reaction to the style of this diagram, so focal figure 22 was intended to provide an alternative representation.

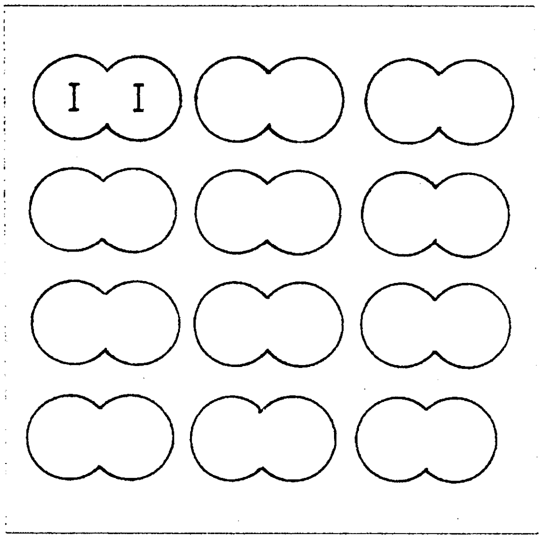


focal figure 11

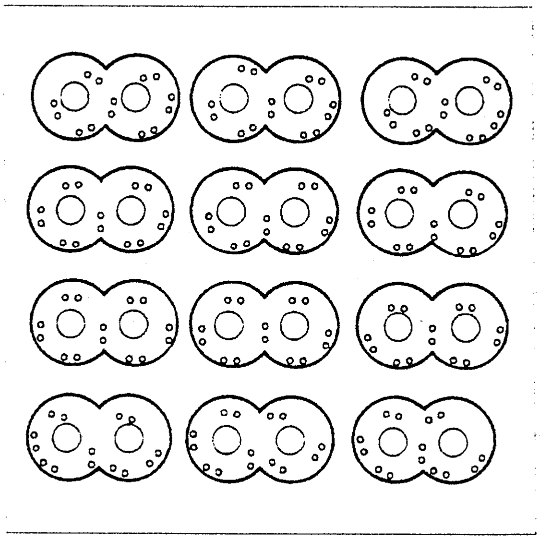


focal figure 22

Focal figure 26 was a variation on focal figure 17, that was intended to provide a suggestion of *why* the molecules should be attracted.

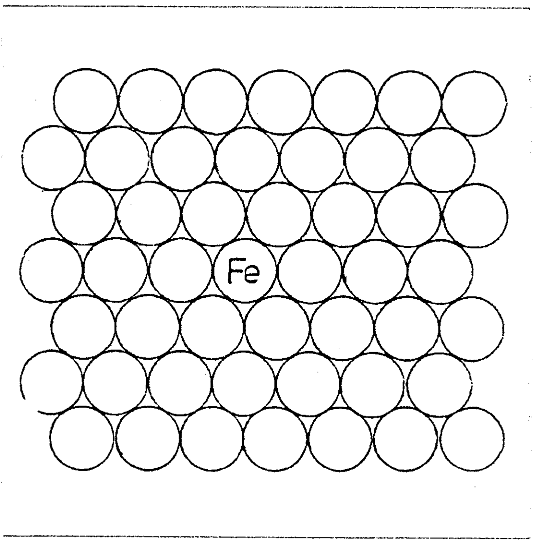


focal figure 17

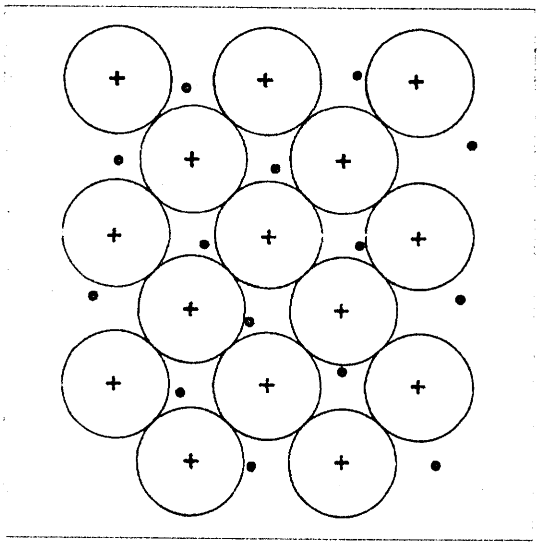


focal figure 26

Similarly, focal figure 80 was meant to offer more detail of metallic bonding than focal figure 6.

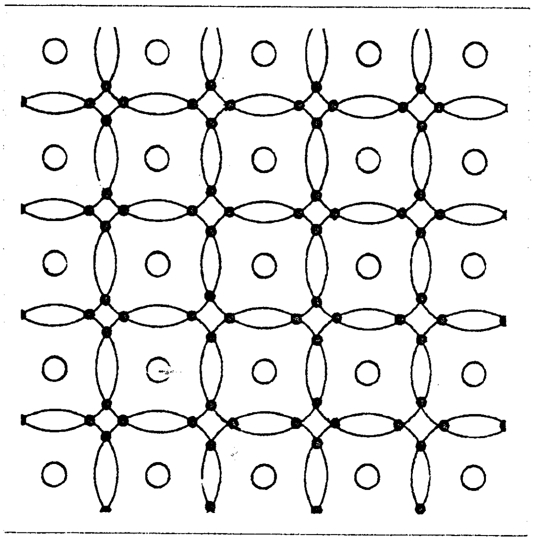


focal figure 6

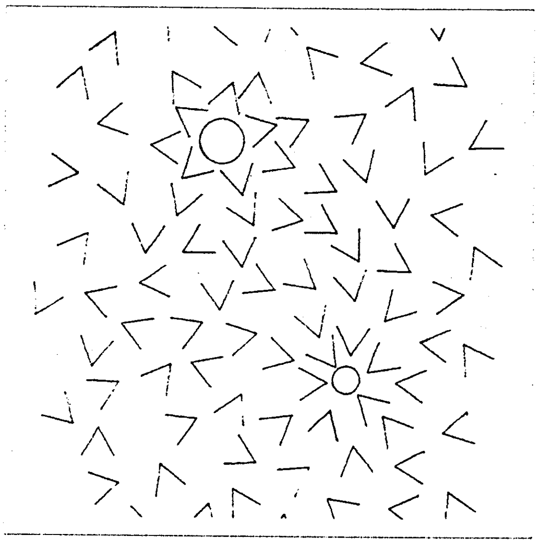


focal figure 80

Some new figures were meant to represent bonding phenomena not covered in the original deck, so focal figure 77 showed a giant covalent lattice, and focal figure 20 represented hydration.

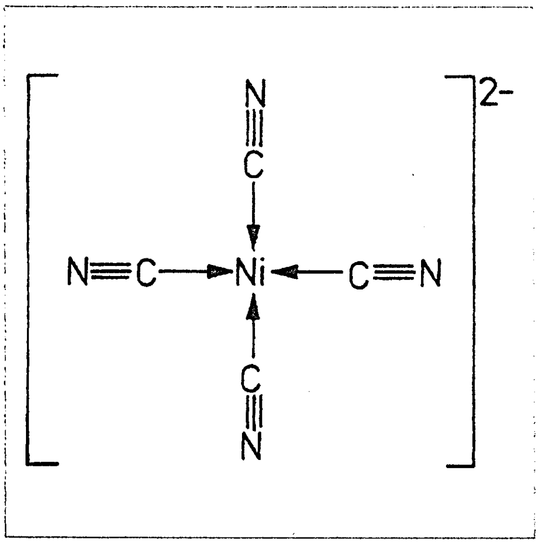


focal figure 77 (detail)

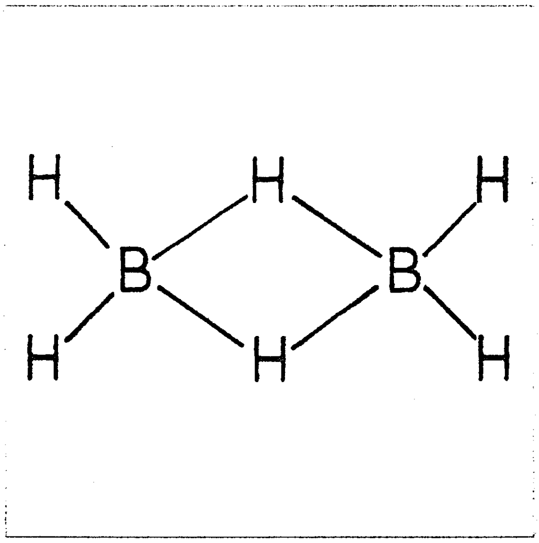


focal figure 20 (detail)

Focal figure 31 represented dative bonding in a complex ion, and focal figure 34 showed a substance with - from a valence bond viewpoint - unusual bonding: diborane. The latter example of a 3-centre-2-electron bond was included in an attempt to faze Brian, who did not appear to be particularly challenged by the interviews. This was only partially successful, as after an initial difficulty matching the number of bonds shown to the number of valence electrons available, Brian concluded correctly that he was dealing with *banana bonds* (B3.1072).

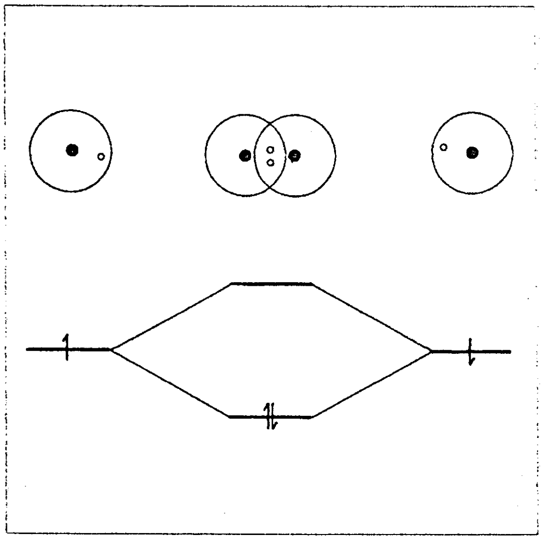


focal figure 31

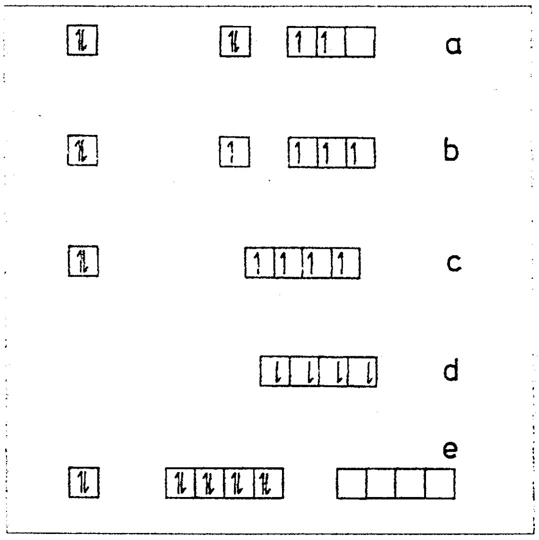


focal figure 34a

Some of the additional figures, such as focal figures 18 and 30, were meant to provide a more explicit context for discussing orbital ideas.

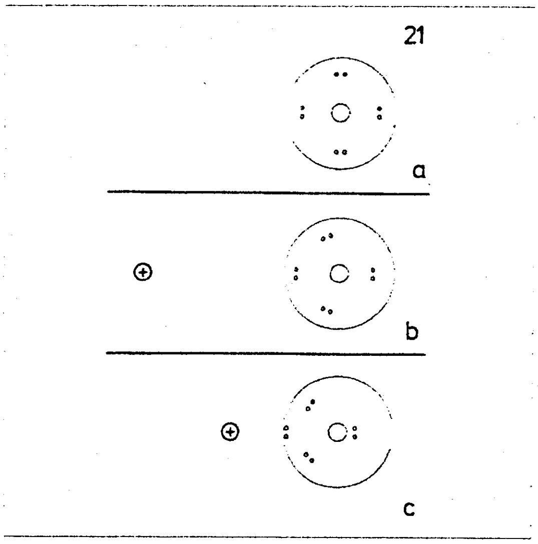


focal figure 18

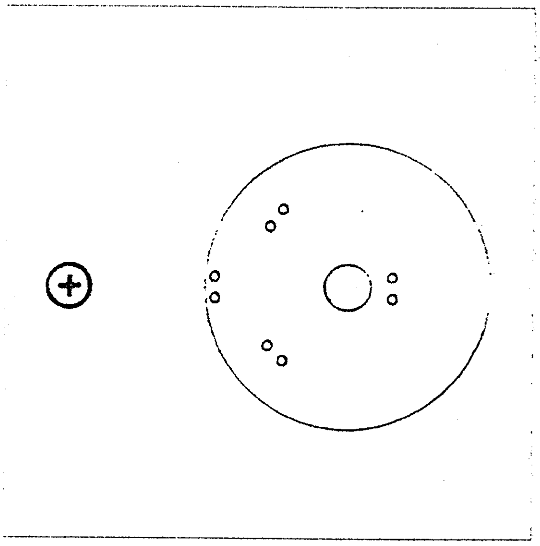


focal figure 30

Other figures were intended to focus student thinking on the electrostatic nature of interactions at the molecular level, so that focal figure 21 represented polarisation.

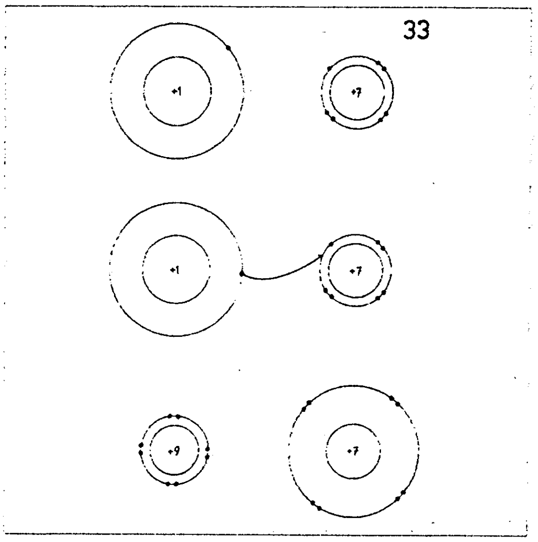


focal figure 21

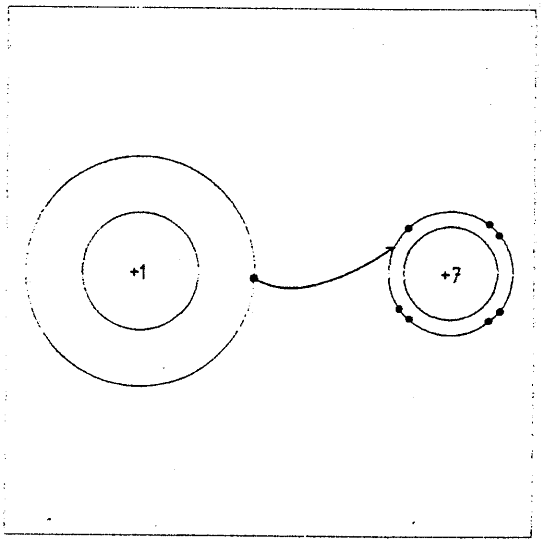


focal figure 21 (detail)

Focal figure 33 represented electron transfer between atoms of different core charges, to provide a context for discussing electron transfer in electrostatic terms.

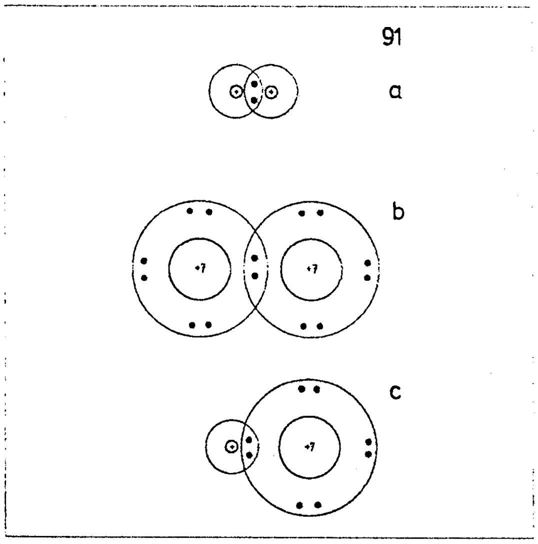


focal figure 33

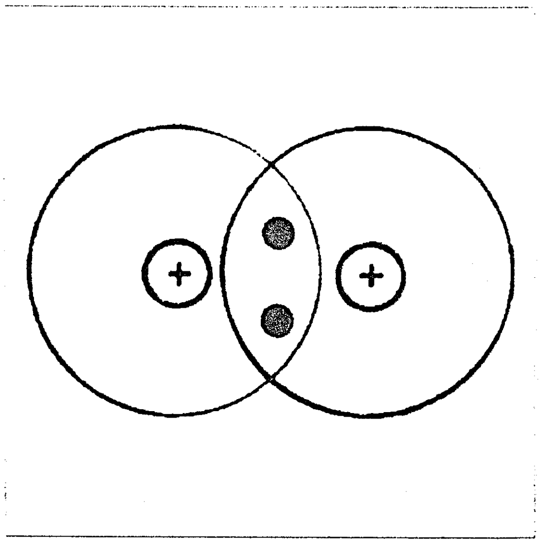


focal figure 33 (detail)

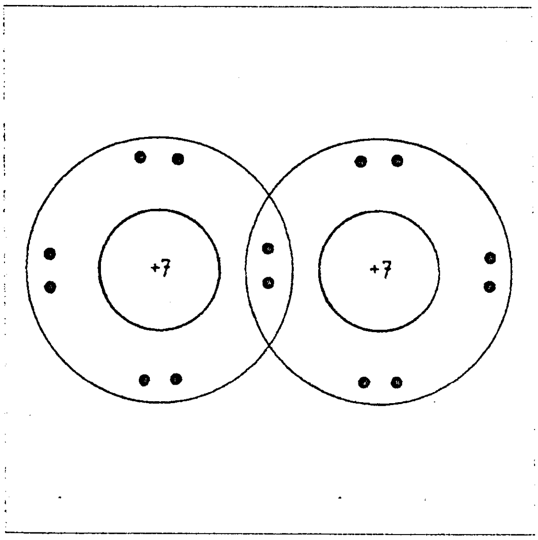
As the significance of 'octet thinking' (see chapter 11) amongst colearners emerged during analysis, some diagrams were prepared to challenge this. Focal figure 91 was meant to provide a basis for discussing the reaction between hydrogen and chlorine where the rationale that bonding took place to give full shells might be seen to be flawed. The three parts of this figure are shown below, where it can be seen that reactant molecules (hydrogen in focal figure 91 part a and chlorine in focal figure 91 part b) involve atoms with 'full outer shells' as much as product molecules (hydrogen chloride in focal figure 91 part c).



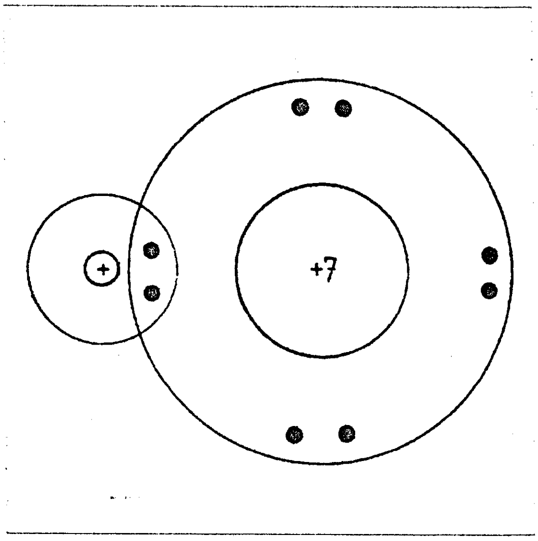
focal figure 91



focal figure 91a

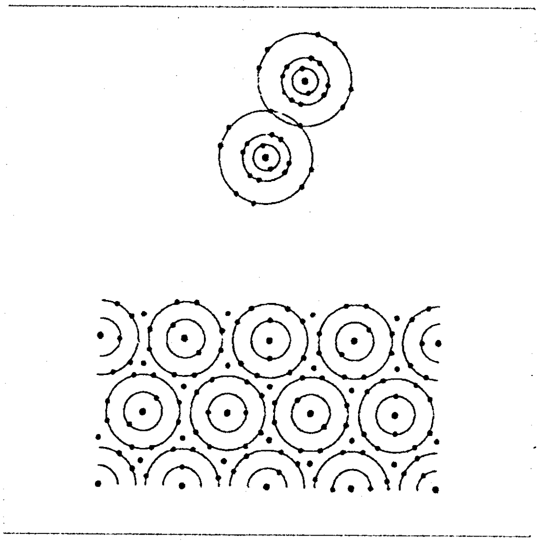


focal figure 91b

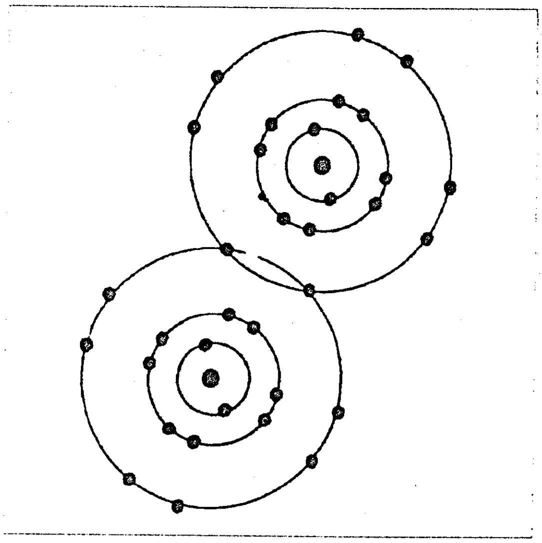


focal figure 91c

In a similar way focal figure 85 provided a context for discussing the reaction between chorine and a metal such as magnesium, where the notion that bonding takes place to give 'full shells' (§11.2) might be challenged.



focal figure 85

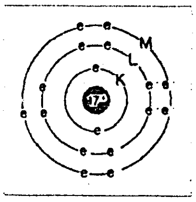


focal figure 85 (detail)

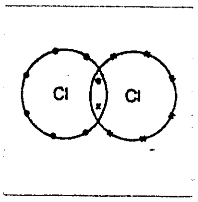
Appendix 17.

Triads of elements (G.C.S.E. level figures) for the construct repertory test.

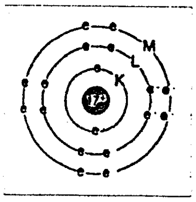
A sample of the text-book diagrams presented as triads of construct elements in the construct repertory test (see chapter 5, §5.1.4).



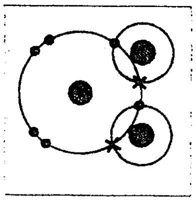
triad element 126



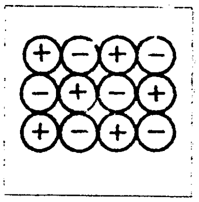
triad element 641



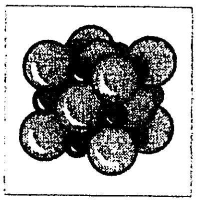
triad element 656



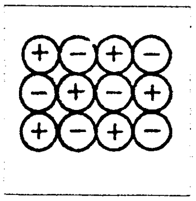
triad element 111



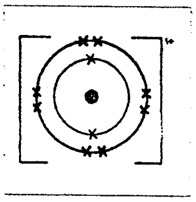
triad element 313



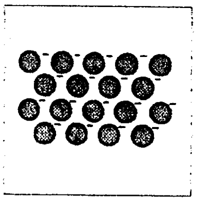
triad element 653



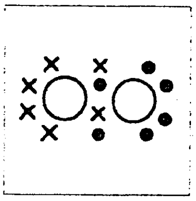
triad element 311



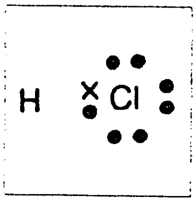
triad element 441



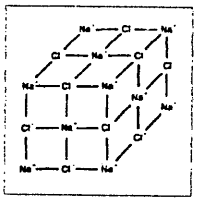
triad element 446



triad element 343

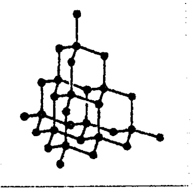


triad element 454

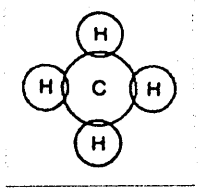


triad element 553

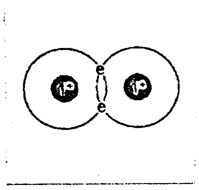
UNDERSTANDING CHEMICAL BONDING



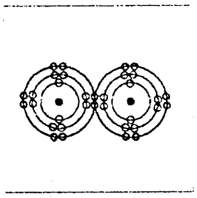
triad element 145



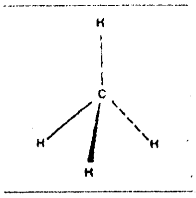
triad element 246



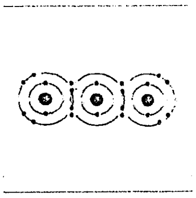
triad element 314



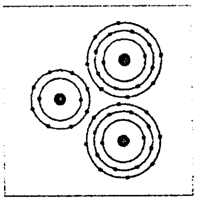
triad element 121



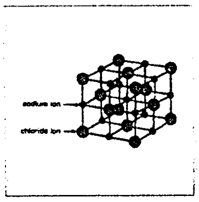
triad element 211



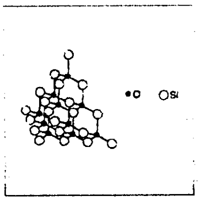
triad element 632



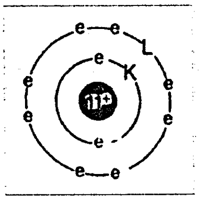
triad element 114



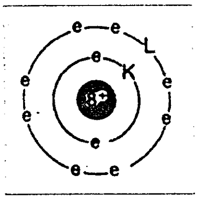
triad element 124



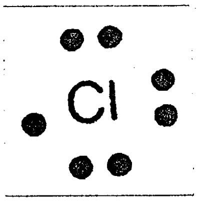
triad element 616



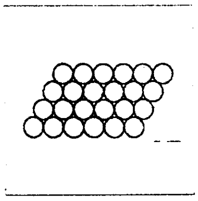
triad element 116



triad element 341



triad element 531



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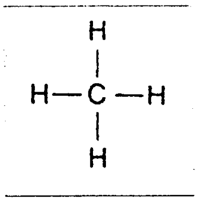
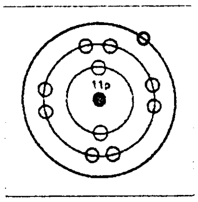


triad element 326

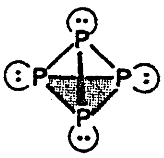


triad element 512

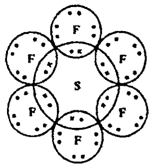
Appendix 18.

Triads of elements (A level figures) for the construct repertory test.

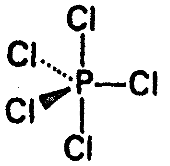
A sample of the text-book diagrams presented as triads of construct elements in the construct repertory test (see chapter 5, §5.1.4).



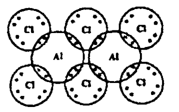
triad element 229



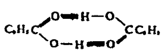
triad element 307



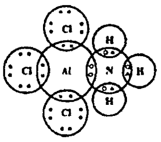
triad element 349



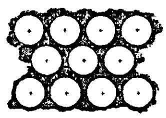
triad element 249



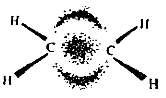
triad element 338



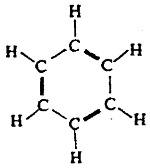
triad element 339



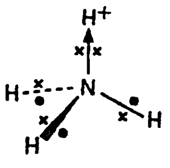
triad element 207



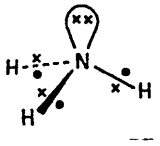
triad element 305



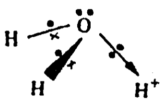
triad element 400



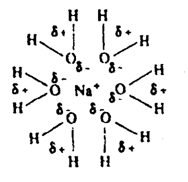
triad element 179



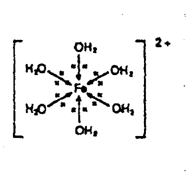
triad element 319



triad element 328



triad element 206



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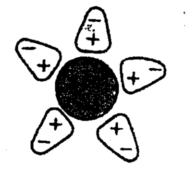
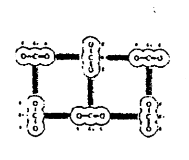
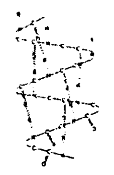


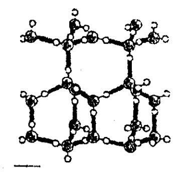
triad element 368



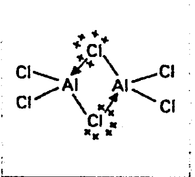
triad element 180



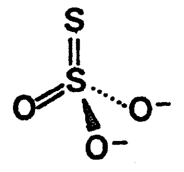
triad element 260



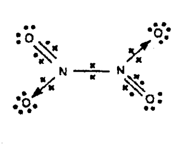
triad element 376



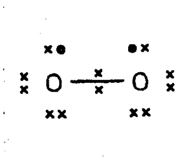
triad element 187



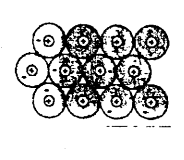
triad element 318



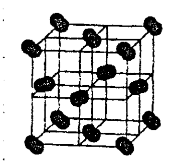
triad element 380



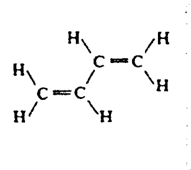
triad element 278



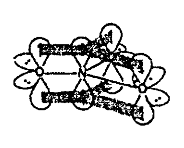
triad element 290



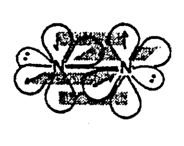
triad element 306



triad element 303



triad element 317

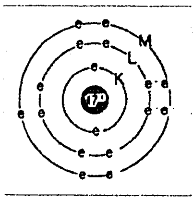


triad element 327

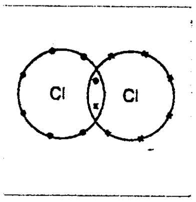
Appendix 19.

An example of a comparison between constructs elicited from different colearners.

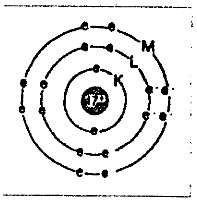
Five colearners were presented with the same triad of 'elements' (cards coded 126, 641 and 656) during the second year of their course (see chapter 5, §5.1.5).



triad element 126



triad element 641



triad element 656

The following constructs were elicited:-

colearner Jagdish (21.10.93):
- ions
- got a core charge of 17+
- got an octet configuration
- in period 3
- in group 7
- tendency to form ions

colearner Noor (11.11.93)
- element
- molecule
- pure covalent bonding
- electrostatic force
- have full outer shells
- ionic bonding

colearner Umar (4.11.93)
- individual atoms
- seven electrons in outermost shell

colearner Kabul (21.1.94)
- loss of electrons
- molecule
- pure covalent bonding
- electrostatic force
- have full outer shells
- ionic bonding

colearner Tajinder (24.1.94)
- show all the shells
- shows a molecule
- shows neutral species
- shared, donated or gained electrons

Appendix 20.

An example of the variation in richness of elicited constructs.

Constructs elicited from students during the construct repertory test were analysed and categorised. Table A20.1 presents the classification scheme that was produced. (The full list of elicited constructs is given in appendix 22, to allow the adequacy of the scheme to be judged.)

The scheme in Table A20.1 allows the richness of constructs to be compared. So for example in Kabul's first term he produced a rich set of constructs when shown elements from the first deck of construct elements (see table A20.2). By contrast Rhea - who later dropped the subject - generated a much less rich set of constructs (see table A20.3).

(It is of interest that a large proportion of the constructs elicited from Rhea concerned aspects of the features of the modes of representation, rather than of the chemically significant features of the species represented. Kabul makes only a few such comments. It is possible that a student having little of relevance to report resorts to commenting on features of the drawings themselves. Alternatively it may be *hypothesised* that a student ignorant of much of the chemical significance of the diagrams is conscious of the way they are drawn, whereas a student who has internalised the symbolism of these types of diagrams *sees through* these features and consciously perceives what is symbolised (c.f. chapter 5, §5.1.3). Although an interesting idea - as it may suggest a way in which the construct repertory technique may have diagnostic value for teachers if developed as a class activity - it has not been possible to explore it in any detail as part of the research programme to date.)

constructs:-

- structural:
  - molecular:
    - shape:
    - others:
  - sub-atomic:
    - nuclear:
    - electronic:
      - c.f. n.g.e.c.:
      - others:
  - crystal:
  - bond type:
  - includes:
- properties:
  - chemical:
    - reactivity:
    - specific:
    - valency:
  - physical:
    - macroscopic:
    - molecular:
      - charge:
      - others:
  - environmental:
- classification:
  - periodic table:
    - electronegativity:
    - block:
    - period:
    - group:
  - state:
  - reagent type:
  - microscopic species:
  - type of substance:
  - specific substance:
  - occurrence:
- diagrammatic features:
- ambiguous/miscellaneous:

Table A10.1
A scheme that could be used when classifying elicited A level chemistry student constructs.

- constructs: **K - 18.11.92**
  - structural:
    - molecular:
      - shape: **tetrahedral arrangement**
      - others:
    - sub-atomic:
      - nuclear:
      - electronic:
        - c.f. n.g.e.c.: **possess octet state**
        - others:
    - crystal: **lattice arrangement**
    - bond type: **covalent bonding**; **bond between different elements**; **ionic compound**; **bond between non-metals**; **polar covalent bond**
    - includes:
  - properties:
    - chemical:
      - reactivity: **can undergo reaction**; **can undergo reaction to form ionic bonds**; **cannot exist on its own**; **high reactivity**; **stable**
      - specific: **forms diatoms**; **displacement of hydrogen by reactive metals**; **can undergo combustion**
      - valency: **electrovalency of -2**; **covalency of 4**; **electrovalency of 1**
    - physical:
      - macroscopic: **low melting point**; **soluble in organic solvents**;**conduction of electricity**; **soluble in water**
      - molecular: **high energy required to break bonds**
        - charge: **charged particle**; **a gain of electrons**; **ionising slowly**
        - others:
      - environmental:
  - classification:
    - periodic table:
      - electronegativity: **metal**
      - block:
      - period:
      - group: **found in group 7**; **found in group 1**; **found in group 8**
    - state: **state of existence is solid**
    - reagent type:
    - microscopic species: **represents an ion**
    - type of substance: **only one element**; **organic substance**; **compound**
    - specific substance:
    - occurrence:
  - diagrammatic features: **we can know the period**; **represents a type of bond**
  - ambiguous/miscellaneous: **can be present in a noble gas**; **ionisation**

Table A20.2.
Data from colearner Kabul, arranged according to the scheme of table A20.1.

- constructs: **R - 11.11.92**
  - structural:
    - molecular:
      - shape: **symmetrical-ish**; **circular**
      - others: **two joined together**; **all clumped together**
    - sub-atomic:
      - nuclear: **got a 17+ charge in the middle**
      - electronic:
        - c.f. n.g.e.c.: **one electron short of a full outer shell**; **full outer shell**
        - others: **three shells**
    - crystal:
    - bond type: **double bonds drawn in**
    - includes: **got orbitals**; **got 'H's**; **two different elements in them**
  - properties:
    - chemical:
      - reactivity:
      - specific:
      - valency:
    - physical:
      - macroscopic:
      - molecular:
        - charge:
        - others:
      - environmental:
  - classification:
    - periodic table:
      - electronegativity:
      - block:
      - period:
      - group:
    - state:
    - reagent type:
    - microscopic species:
    - type of substance:
    - specific substance:
    - occurrence:
  - diagrammatic features: **other shells drawn in** ; **electrons as circles**; **electrons as 'e'**; **say what they are**; **minus signs on some of the 'e's**; **got shading**; **got brackets**; **written**; **got plus signs**; **say how many electrons are shared**; **got plus signs in the middle**; **got charges drawn in**; **3-D drawing**; **simple sketch drawing**; **got a key**
  - ambiguous/miscellaneous: **got structure(s)**

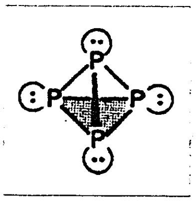
Table A20.3:
Data from colearner Rhea, arranged according to the scheme of table A20.1.

Appendix 21.

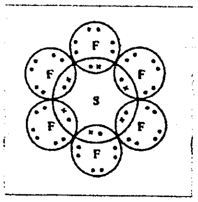
An example of the stability of elicited constructs over time.

Constructs were elicited from co-learner Tajinder using the same triads on two occasions (7/10/93 and 9/5/94) during the second year of his course. Some examples of the constructs elicited were:-

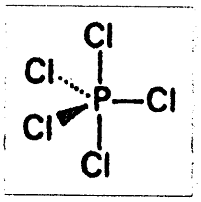
'elements'
229 / 307 / 349



triad element 229



triad element 307



triad element 349

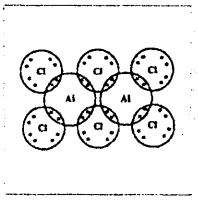
7/10/93

contains phosphorus
all valent electrons used in bonding
shows degree of covalent bonding
contains two or more different atoms

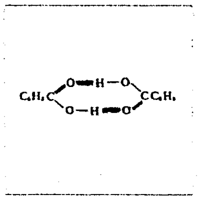
9/5/94

has expanded octet
d-orbitals used in hybrid

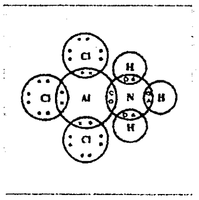
249 / 338 / 339



triad element 249



triad element 338



triad element 339

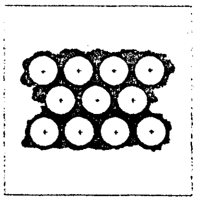
7/10/93

shows degree of covalent bonding
shows hydrogen bonding

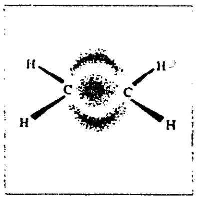
9/5/94

contains dative covalent bonds
intermolecular bonding (hydrogen bonding)
dimer

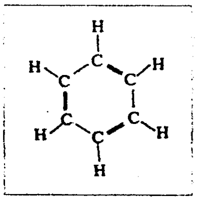
207 / 305 / 400



triad element 207



triad element 305



triad element 400

7/10/93

shows carbon-carbon bond
hydrocarbon
are bonded metallically
contain delocalised electrons
contain π and σ bonds

9/5/94

delocalisation of electrons
hybridisation takes place
undergo electrophilic addition reactions
undergo electrophilic substitution reactions

Appendix 22.

Constructs elicited by Kelly's method of triads.

A complete list of constructs elicited from colearners during the research:-

Colearner **Brian** (chemistry undergraduate {A level student 9.90 - 6.92}.)

6.7.93 *[pilot for deck 2 - see appendix 18]*
specific compounds; contain oxygen; charges; show specific bonds; show interaction between a central positive atoms and negative end of molecule; delocalisation shown; transition metal complex; homonuclear molecules; show named specific atoms; shows double bonds; shows electrons; diatomic; shows electron cloud; organic; inorganic; interactions within a crystal; obviously aromatic; polymer; contains double bonds; sp^3 hybridisation; two central atoms; dimer; clearly showing double bonds; radical; clearly charged; tetrahedral; contains phosphorus; acids; contains hydrogen; contains nitrogen; shows hydrogen bonding; shows shape of molecule; shows electron density; adduct; shows structure of crystal; is a ring; contains electron-deficient bond

Colearner **Edward** (A level student 9.91 - 6.93)

29.10.92 *[pilot for deck 1 - see appendix 17]*
two orbitals; three protons; no neutrons; noble gas configuration; form ionic compounds; three electron orbitals (shells); unreactive; gas at room temperature; crystalline solid; electronegative; dense; reacts with water; neon; orbital lobes; ions; anions; three-dimensional; multiple bonds; double bond; organic; hybridised; pi-bond; localised pi-bond; stable; eleven protons; metal; one valence electron; simple covalent; single element; ring; macromolecular; tetrahedral; covalent; high melting point solid; dissociates in water

Colearner **Jagdish** (A level student 8.92 - 6.94)

04.11.92 [*deck 1 - see appendix 17*]
ionic bonding; contains metal; solid at room temperature; soluble in water; compounds; metals; high melting point; gases at room temperature; have isomers; forms ions; atoms; ions; fairly reactive; group 1; covalently bonded; electrical current; produce anions; produce cations; electrophile; if dissolves in water, would have acidic properties; nucleophile; contain oxygen; diatomic molecule; harmful to the ozone layer; helps form free radicals; halogen; oxidising agent; metal ions; inert gas; stable

21.10.93 [*deck 1 - see appendix 17*]
ions; got a charge of 17+; got an octet configuration; in period 3; in group 7; tendency to form ions; hydrogen bonding; ionic compounds; forms ionic lattices; liquid at room temperatures; have metallic structures; body centred cubic; metallic bonding (delocalised orbitals); overall uncharged substance; consist of just a metal; conduct electricity; conduct heat; diatomic; when aqueous an acid; sodium chloride structure; gas at room temperature; consists of group 6 element; nucleophile; proton donor; organic substance; compound; shape of molecule in a tetrahedron; sp^3 hybridisation; bond angle 105.28; undergoes free radical attack; exists in natural gas; homologous series alkane; lattice structure; van der Waals forces; double bond; contains carbon; homologous series alkene; undergoes electrophilic attack; decolourizes bromine water; soluble in polar solvents; covalent bonding; forms crystals; made-up of metalloid; element; period 2; inert gas; halogen; metal; can form positive ion; s-block element; electropositive; polar bond

28.10.93 [*deck 2 - see appendix 18*]
have phosphorus in them; have group 7 elements; show lone pair of electrons; carry out nucleophilic substitution; form a complex ion; dimer; hydrogen bond; have aluminium in them; acidic properties; basic properties; metallic bonding; delocalised electrons; double bond; aromatic compound; homologous series alkane; electropositive; organic compound; attacked by free radical (guess); ions; contains oxygen; solvent for acid base reactions; hydrated ions; salt solution (part of); transition metal; dipole shown; protein structure; van der Waals forces; gas; macromolecule; polymer; secondary structure; lattice; contains chlorine; dative bond; diatomic; ionic structure; covalent bonding; can undergo cleavage; high melting point; contains a metal; aids combustion; triple bond; diazonium bond; contains nitrogen; sp hybridisation; sp^2 hybridisation; found in fertilisers; undergoes electrophilic attack

Colearner **Kabul** (A level student 9.92 - 6.94)

18.11.92 *[deck 1 - see appendix 17]*
possess octet state; stable; can be present in a noble gas; found in group 7; found in group 1; found in group 8; can undergo reaction; can undergo reaction to form ionic bonds; forms diatoms; metal; represents an ion; charged particle; we can know the period; represents a type of bond; only one element; a gain of electrons; cannot exist on its own; low melting point; electrovalency of -2; covalency of 4; soluble in organic solvents; conduction of electricity; covalent bonding; bond between different elements; ionisation; soluble in water; displacement of hydrogen by reactive metals; organic substance; ionic compound; high energy required to break bonds; state of existence is solid; high reactivity; bond between non-metals; can undergo combustion; electrovalency of 1; lattice arrangement; tetrahedral arrangement; compound; polar covalent bond; ionising slowly

20.1.94 *[deck 1 - see appendix 17]*
loss of electron; ions; group 1 metals; group 7 elements; gain electrons; show sub-shells; show ionic characteristics; 3-dimensional diagram; you can see elements of which group are involved; shows ionic bonding; shows metallic bonding; mobile electrons present; shows cation; shows covalent bonding; shows polar covalent bonding; shows the distribution of electron density; sp^3 hybridisation; macromolecular structure; organic molecule; double bond present; possibility of electrophilic addition reaction; made up of more than one atom; ionic lattice; shows coordination number; consists of a halogen; shows it's a single atom present
[deck 2 - see appendix 18]
shows 3-dimensional diagram; shows presence of lone pair of electrons; trigonal bipyramid; tetrahedral; octahedral; bonds present in equatorial position; uses V.S.E.P.R.T.; dative bonding present; shows dimerization; shows hydrogen bond; organic molecule; Lewis base; organic acid; metallic bonding; can undergo electrophilic addition/substitution reactions; delocalisation of electrons; shows the presence of sigma and pi bonds; pyramidal molecules; shows the presence of ligands; shows the presence of solvation; complex ions; free molecules; looks like lattice structure; delocalisation of charge; covalent bond present; van der Waals forces; simple molecule; sp hybridisation

Colearner **Lovesh** (A level student 9.92 - 6.94)

27.11.92 *[deck 1 - see appendix 17]*
show each orbital in atom; show electrons as 'e' s; shows a positive nucleus; complete outer shell; symbol for atom shown; name of orbitals shown; electrons shown as negative, protons shown as positive; two atoms involved in covalent bonding; protons shown as positive; can identify which compounds they are (/it is); contain three orbitals; contain two orbital; stable atoms; one electron in outer-shell; eleven protons; seventeen protons; represent sodium; represent chlorine; represented as 3-D shape; involve two atoms combined; show electrons; what we learn at GCSE; what we learn at A level; orbitals represented as dumbbells; shows different types of orbitals; show what elements are involved; compounds in the form of a lattice; ion(s); show ionic bonding; shows the charge on each atom; involve covalent bonding; atoms stuck together; atoms repelling each other; involve atoms of the same element

Colearner **Mike** (first year A level student 9.92 - c.3.93)

19.11.92 *[deck 1 - see appendix 17]*
able to form bonds; dealing with electrons and protons; bonds where electrons are being shared; a pair of electrons being shared between two atoms; molecule; show grouping of electrons; show structure when two types of atom are combined; show ions; paper drawn structure of a molecule; show orbitals; complete atoms; complete outer shell; double bonding; same atoms joining; three dimensional structure; bonding of different atoms; both hydrogen and nitrogen; four bonds; zero charge; hydrogen and carbon molecules

Colearner **Noor** (A level student 9.92 - 6.94)

06.11.92 *[deck 1 - see appendix 17]*
group 1 metals; lose one electron to become stable; could join with group 7 non-metal 1:1; in form of a bond; covalent bond; stable; show s-orbitals; covalent bonding with one pair of electrons; non-metals; more than one orbital; single bond; use p and s orbitals; involve hybridisation; compound; one or more unhybridised p-orbitals; ion; forms a tetrahedral shape with angles of 109.5°; neutral; atomic number = 8; period 3; group 7 elements; bonding involving carbon; ionic bonding; lattice; involve two different elements; charged; ethene; one double bond between two carbon atoms; ring shaped structure; alkene; CnH2n; can be formed by dehydration; double bonds; hydrocarbon; oxidise to form CO2 and water; used as monomer to make plastic; exists as S8 atoms

11.11.93 *[deck 1 - see appendix 17]*
element; molecule; pure covalent bonding; electrostatic forces; have full outer shells; ionic bonding; covalent/polar bonding; transfer of electrons; sharing of electrons; ions; metal; van der Waals forces; show a form of lattice; one non-metal, one metal; diatomic molecule; compound; two different elements; species shown have same electronegativity; double bond; alkene; attacked by electrophile; will dissociate in water; in period 2; in group 7; species show different electronegativity; alkane; get tetrahedral arrangement; angles are 109°28'

18.11.93 *[deck 2 - see appendix 18]*
showing trigonal bipyramidal structure; involve two different atoms; phosphorus in oxidation state 5; phosphorus molecule; showing lone pairs; showing tetrahedral structure; showing polar bonding; example of expanding the octet; showing a dimer; showing hydrogen bonding; dative covalent bonding; showing metallic bonding; alkene; delocalised; undergoes electrophilic addition reactions; undergoes electrophilic substitution reactions; reacts with bromine water; will undergo alkylation; will undergo acylation; got a ring structure; shows resonance between two canonical forms; shows double bond; aromatic compound; shows trigonal structure; positive charge on hydrogen; ions in solution; showing electrostatic attraction; induced dipoles; ion; intramolecular hydrogen bonding; extramolecular hydrogen bonding; showing an order of two in its bonding; linear molecule; shows slightly charged atoms; resonance hybrid; showing van der Waals; diatomic molecule; sharing electrons; showing a lattice structure; shows triple bond; sp hybridisation; sp^2 hybridisation; alkyne

Colearner **Paminder** (A level student 6.92 - 7.94)

12.11.92 *[deck 1 - see appendix 17]*

seven electrons in the outer-most shell; first shell is full, i.e. contains 2 electrons; second shell is full, i.e. contains 8 electrons; three shells present; neutrons present; chlorine atoms present; in group 7; in period 3; charge of 17+; two inner shells; great loss of electrons; great number of initial electrons - before any were lost; number of electrons is the same as value of charge; got four orbitals which help it to bond with four other substances; tetrahedral; hydrogen bonding present; covalent bonding present; double bond present; 2s orbital present; pi-bond present; 2p orbital present; charge present; three dimensional; ionic bonding present; lattice structure; carbon present; chlorine present; two different elements present; a type of tetrahedral structure; cube-like structure; metal and non-metal present; positive charge present; negative charge present; more than two atoms present; shells shown; in transition state; nucleus shown; type of bonding shown; neutral species

Colearner **Quorat** (A level student 9.92 - 6.94)

5.11.92 *[deck 1 - see appendix 17 - see appendix 17]*

one electron outer shell; covalent bonding; atoms; gas; lattice; ten electrons; bond; charged; one type of atom or ion; two hydrogens; one oxygen; single element; contains nitrogen; four covalent bonds; contains halogen; closely packed; dislocation; double or triple bond; orbitals shown; molecular structure shown; elements shown; four bonds; double bond; water; contains pi-bond; four hydrogen; double covalent bond; contains carbon; single atoms; contains hydrogen

Colearner **Rhea** (A level student 9.92 - 6.94 (dropped Chemistry during first year)

11.11.92 *[deck 1 - see appendix 17]*
one electron short of a full outer shell; other shells drawn in; electrons as circles; electrons as 'e'; say what they are; got a 17+ charge in the middle; three shells; full outer shell; minus signs on some of the 'e's; got orbitals; got shading; got 'H's; symmetrical-ish; got structure(s); got brackets; written; got plus signs; two joined together; circular; say how many electrons are shared; got plus signs in the middle; all clumped together; got charges drawn in; double bonds drawn in; two different elements in them; 3-D drawing; simple sketch drawing; got a key

Colearner **Tajinder** (A level student 9.92 - 6.94)

10.11.92 *[deck 1 - see appendix 17]*
one electron in outer shell; neutral species; ion; atom; electrons in K, L and M shells; unstable; same number of protons as electrons; shows rough placement of electrons in orbitals; molecule; contains bonds; covalent bonds; contain two different types of atom; ionic bonding; solid at room temperature; molecule of water; pass electric current; contains two or more different types of atom; shows s and p orbitals; hydrocarbon; diatomic molecule

18.05.93 *[deck 1 - see appendix 17]*
shows shells; more than one electron; atom; ion; need one extra electron to have full outer shell; not have noble gas configuration; in period 3; element is magnesium; show noble gas configuration; in period 2; don't have full outer shell; show type of bonding; have full outer shell; contains only chlorine; contains one type of element; shows covalent bond; shows ionic bond; shows diatomic molecule; shows hybrid bonds; shows metallic bonding; shows lattice structure

7.10.93 *[deck 2 - see appendix 18]*
contains phosphorus; all valent electrons used in bonding; shows degree of covalent bonding; contains two or more different atoms; shows hydrogen bonding; show carbon-carbon double bond; hydrocarbons; are bonded metallically; contain delocalised electrons; contain pi and sigma bonds; contain hydrogen ion; donates both electrons in order to form bond; metal ion present; show attraction for ∂-ve part of molecule; show van der Waals forces; contain double bond; diatomic molecule; contains lone pair of electrons

24.1.94 *[deck 1 - see appendix 17]*
shows all the shells; shows a molecule; shows neutral species; shared, donated or gained electrons; shows molecular arrangement in lattice structure; shows delocalised electrons; represents a type of bond; diatomic molecule; shows strong characteristics of ionic bonding; gases at room temperature; can be made in the laboratory

[deck 2 - see appendix 18]
contains phosphorus; stored underwater; to produce an unreactive atmosphere; contains one or more different element; represents dative covalent bond; shows hydrogen bonding; contains delocalised electrons; contains only covalent bonding; shows ions; contains sigma and pi bonds; hydrocarbon; conducts electricity; contains lone pair; shows hydration of metallic element; element hydrated with ∂- side of H_2O; shows van der Waals forces; diatomic molecule

9.5.94 *[deck 2 - see appendix 18]*
has expanded octet; d-orbitals used in hybridisation; contains dative covalent bonds; intermolecular bonding (hydrogen bonding); dimer; delocalisation of electrons; hybridisation takes place; undergoes electrophilic addition reactions; undergoes electrophilic substitution reactions; acting as bases (accepting proton); lone pair influence on bond angle; specific arrangement of ligands; intramolecular bonding present; hydrogen bonding present; resonant structure(s); van der Waals forces exist in species; sp hybridisation

Colearner **Umar** (A level student 9.92 - 6.94)

25.11.92 *[deck 1 - see appendix 17]*
unstable; full shells; one covalent bond; four covalent bonds; three shells; two shells; eleven protons in the nucleus; two covalently bonded oxygens; two covalent bond; water molecules; hydrogen in; giant structures; difficulty in breaking bonds; probably charged; alkane; positive water molecule; ionic bonds; bonds present

Appendix 23.

A sample of transcribed interview dialogue.

In chapter 5 (§5.2.2) the approach to transcribing interview data was described. The following sample extract is from the beginning of Carol's second interview. No limited extract of transcript from any one colearner could be said to be typical of the transcriptions undertaken as colearners had distinct styles of answering questions. (One distinctive aspect of Carol's interviews was her particular tendency to suggests ideas and then, on reflection, change her mind almost immediately. This may be seen at C2.16 and C2.42.) This notwithstanding, this sample is not especially atypically, and shows a number of common features (such as overlapping speech, poor grammar, unfinished thoughts etc.) A range of other extracts (albeit mostly much shorter) are used to illustrate the *results* section of the thesis (chapters 7 - 11 and associated appendices).

C2.

1 I: If you'd like to look at number one, erm basically, this is the same question we asked you before really, is there any bonding present?
2 C: No.
3 I: No. Can you tell me what holds the atom together?
4 C: Erm, the attraction between the electrons and the positive nucleus.
5 I: Okay. What holds the nucleus together?
• • • • • [pause, c.5s]
6 C: Is, is it something to do with mass defect, or something? That's the energy used to, I don't know really, what holds the nucleus together.
7 I: But you reckon, what was it that holds the atoms together?
8 C: The attraction between the electrons and the positive nucleus.
9 I: And what kind of attraction is that?
10 C: Erm,
• • • • • • • • • • • •
C: well it's directional, isn't it? But I don't know what exactly attraction it is.
11 I: Would you say there's any force involved?
12 C: Yeah, oh it's that, is it something to do with that Q-n-times-Q-e-over-r-

squared, or something?

13 I: Coulomb's law?

14 C: Coulomb's law.

15 I: What kind of force is that then?

16 C: Erm, oh no, that's the attraction between two, atoms, isn't it, that one, I think. Yeah it, no it isn't! No it isn't! That's erm, the force between the outer election, electron and the nucleus. How much force is acted on that electron.

17 I: Right, so that law,

C: yeah

I: force is proportional to, first charge times second charge, divided by square of the distance,

C: Yeah.

I: you say that law applies to, so in this diagram it would be the force between that outer electron there,

C: Yep.

I and that nucleus there in the middle. The amount, the size of that force would be given by that relationship, would it?

18 C: Yeah.

19 I: But what about the force > between this electron >

20 C: < Oh the same, the same! <

21 I: Same relationship

C: Yeah.

I: for that as well, what about the inner electron and nucleus. Would that be given by that?

22 C: Yeah.

23 I: What about the repulsion, say, between this electron and this electron - in different shells? Would that be given by that?

24 C: I suppose you could find the difference, couldn't you? But you could only

25 I: Ah, but could you use that relationship? Coulomb's law - could you apply Coulomb's law to two electrons?

26 C: No, 'cause I think you need a constant in the equation, so its, the force is equal to something, so they're proportional.

27 I: So because of that, it only applies to electrons and the nucleus, does it? Not electron and electron?

28 C: Well,

• • •

C: I don't know really.

29 I: Okay, what's in the nucleus?

30 C: Protons and neutrons.

31 I: Right, are they attracted to each other, or repelled to [sic] each other, or?

32 C: No, they just, well neutrons haven't got any charge, so,

32 I: Okay, if neutrons haven't got any charge, what holds them in the nucleus, why don't they just fall out?

33 C: Erm, I dunno, because you would think that a nucleus wouldn't, wouldn't be there really because, it's all protons and they're * repel, 'cause they're the same charge.

34 I: So, so why don't they repel?

• • • •

35 I: Can you apply Coulomb's law to two protons?

36 C: Don't know.

37 I: But you think they should repel?

38 C: Yeah.

39 I: Do they, do they seem to?

40 C: I think they do. But,

I: Uhm?

C: there's another force, might be to do with electrons around the outside that holds it together.

41 I: Ah, so somehow the electrons in these outer shells hold the nucleus together, do they?

42 C: Or it might, or, it might be something to do with,

• • • •

C: no, I was going to say something about the interaction of the orbitals, but protons haven't got any orbitals, so.

43 I: Hm. Do you think there might be some other force holding the nucleus together?

44 C: Not exactly in the nucleus, but acting from outside, on it. Which, I suppose, must be the electrons.

45 I: Right, but are there any bonds involved in this process?

46 C: No.

47 I: No. But there are forces involved?

48 C: Yeah.

...

Appendix 24.

Diagnosis of Noor's use of fundamental chemical categories.

The use of the *construct repertory test* (§4.7) revealed that Noor construed some chemical terms differently to their CURRICULUM SCIENCE meaning.

Noor was a very bright and hard-working student, but she brought with her from school some unusual meanings for certain fundamental chemical terms, and this was revealed through the work with the triads.

Noor presented a construct **lattice**. According to Noor a figure of a metal did not exhibit this attribution, but a number of simple molecules did. In an interview she confirmed that sulphuric acid, water and benzene would all have lattices. It appeared that Noor's construct of **lattice** related to the bringing together of all the elements in a compound, rather than the usual structural connotation.

She applied the construct **compound** to diagrams showing a range of (chemical) elements, and when interviewed later reiterated that H_2, Cl_2, O_2 and S_8 could be called **compounds**, but not **elements**.

Despite having this brought to her attention, and continuing through the course very successfully, one year later Noor was presented with triads and again she gave inappropriate discriminations using the construct **compound** as well as **molecule**. She was then asked to use the terms **element**, **molecule**, **ion** and **compound** with a whole series of *triad elements* (i.e. a hypothesis was formed in the mind of the researcher, and tested). Inspection of the data showed that for Noor these categories were (nearly always) used as exclusive: a *triad element*:

could *not* show a **molecule** *if* it showed a **compound**
could *not* show **ions** *if* it showed a **compound**
could *not* show a **compound** *if* it showed a **molecule**
could *not* show a **compound** *if* it showed **ions**

So:

- three *triad elements* representing ionic lattices (124, 311, 553) were construed as **compounds**, but not as **ions**;
- a water **molecule** (*triad element* 111) was not construed as a **compound**;
- two representations of ions (*triad element* 313: Ca^{2+} & $2Cl^-$; and *triad element* 114: Mg^{2+} & $2Cl^-$) were considered **ions** but not as **compounds**, as was a representation of a polar hydrogen chloride molecule (*triad element* 454);
- three representations of discrete molecules (*triad elements* 211, 246, 326) and a macromolecule (*triad element* 616: silica lattice) were construed as **compounds** but not as **molecules**.

In Kelly's terms Noor was using these four terms as *preemptive constructs*,

> "A construct which preempts its elements for membership in its own realm may be called a preemptive construct. ... This is a pigeonhole type of construct; what has been put into this pigeonhole cannot be simultaneously be put into any other."
> (Kelly, *1963 {1955}*, p.153-4.)

The difference between Noor's discriminations and the orthodox use of the terms was discussed with her, with particular emphasis on the distinction between the molar and molecular levels of studying chemical species - that is that although compound and element are exclusive terms an element may be made of atoms or molecules; and a compound of molecule or ions.

One week later her use of the constructs had changed, so that she was *generally* able to apply the labels in the accepted way (i.e. as *constellatory* rather than *preemptive* constructs.) She was now able to construe a *triad element* as being both **ions** & **compound** (e.g. *triad element* 313: calcium chloride, previously not construed as a **compound**), **molecule** & **element** (e.g. *triad element* 145: diamond type lattice, previously not construed as a **molecule**), or **molecule** & **compound** (e.g. *triad element* 246: methane molecule, previously not construed as a **molecule**.)

The change in discriminations was significant, but the new judgments were not completely orthodox: the water molecule was now a **compound** but not a **molecule**. Also in no longer seeing the constructs as *preemptive* Noor now construed the hydrogen chloride molecule (with its bonding electrons shown as completely over to the chlorine) and the sodium chloride lattices as representing **ions**, **compounds** *and* **molecules**: where the orthodox use sees ions and molecules as exclusive categories! (Noor is in good company - the French scientist Daudel is translated as referring to the "molecular ion symbolised NO_2^+" as "this molecule" {1990, p.90}.) Construing molecules within an ionic lattice appears to be common among students (§11.4.3).

Appendix 25.

A sample of transcribed colearner dialogue.

In appendix 23 a sample of interview transcription was presented. The colearner dialogues were transcribed following the same format (§5.2.6).

As an example, this appendix presents an extract from the transcript of Jagdish and Tajinder attempting to answer a past examination question. The extract (starting at tape counter 196 on the cassette tape) illustrates that these colearners had difficulty making sense of part of a question which asked about the bond strengths in diatomic molecules of sodium and cæsium. As sodium and cæsium are usually met as metallic structures this was a difficult question, where the examiner was looking for the candidates to realise that by analogy with diatomic hydrogen, in the vapour phase diatomic molecules of group 1 elements could be found under certain conditions.

Although Jagdish and Tajinder did not come to a satisfactory answer in this extract, and moved onto the next part of the questions, the sample illustrates the general nature of this *slice of data* (§4.4.2), which tended to include incomplete sentences, overlapping speech, 'sharing' of sentences, and negotiation of both the meaning being constructed and the procedure (i.e. whether *a point* has been dismissed, accepted or is still moot, whether a question is answered, being answered, or being given up on, which aspect of a question or possible relevant concept from the chemical toolbox to consider next).

JT1.A196

1 T: C'mon, read it out then.
2 J: [reading question] The molar enthalpies of bond association, dissociation of the molecules H_2, Na_2 and Cs_2 are 436, 73 and 44 kJ per mole, respectively. Discuss the nature of the bonds in these molecules, and the reactions, and the reasons for differences in their, er, strengths.
3 T: All right then, erm,
• • [pause, c.2s]
T: we've got H_2, and er, H_2
4 J: Wait a minute, the higher the bond enthalpy,
T: Yeah.
J: shouldn't they be negative values?
• •
5 T: > It doesn't matter, does it? >
6 J: < No, they're bond < dissociation.
• • •
7 T: And they're broken up.
8 J: Mm, so it's endothermic.
• • • • • •
9 J: So the higher bond dissociation, the more stable, the,
10 T: compound, no molecule,
11 J: the angle, bond yeah. Hydrogen, why is it so strong?
• • • • • • • • •
12 T: First, first of all it's in a gaseous state, isn't it?
13 J: Mm.
14 T: Hm:m.
15 J: Is it because it's such a small molecule, so you have, and because the nucleuses are gonna be so close to each other? No, but that's going to repel, innit?
16 T: Yeah, but still, if it's like, if it's got erm strong bond between it, because it's got equal negativity, electronegativity hasn't it, so the, erm, electron density is like
17 J: Yeah, but you say that for Na_2 or Cs_2 as well, innit? 'cause they're, you know, > how do you know it's going to be >
18 T: < no but this, this < is a different type of bond, isn't it?
19 J: M:m.
20 T: And so is that.
• •
21 J: [Huh.]
22 T: Now we can explain these two can't we?
23 J: What Na_2 and Cs_2?

24 T: Yeah.
25 J: Ionic, metallic.
26 T: Yeah they're metallic bonds, right. So they're in erm metallic structures, so they've got, erm > delocalised >
27 J: < delocalised <
28 T: electrons, right.
29 J: But why is Cs_2 smaller, weaker than Na_2 bond?
30 T: Erm, because Cs_2 has got a larger atom, hasn't it?
31 J: Mm.
32 T: Erm, it's a larger atom

•••••••

T: it's a larger atom, takes less energy to break the bonds break the bonds between them doesn't it? Is that, what group is that in? Is it in the same group as sodium?
33 J: Cæsium, group 1 or group 2, can't remember.
34 T: Yeah, so it's not going to make that much difference, is it?
35 J: No.
36 T: If it's got one electron, that it's like delocalised, yeah? And if it's got a bigger erm atom, it's got the same core charge, hasn't it, so it's got the same strength of pulling the electrons in, well,
J: oh because but because it's smaller, you've got more distance, so you've got less effect,
T: so therefore it's easier,
J: M:m.
T: to break up, Cs_2
J: so that's the reason H_2 is so strong, because it's such a small - atom compared to the others
T: M:m.
J: so you've got less distance, so you've got more effective,

••

T: no, 'cause it > doesn't work, does it? >
J: < you get more < effective, mm, yeah.
37 T: Because this is, this is different kind type of bond, 'cause this is a covalent bond, and these are two metallic bonds. 'Cause it says, discuss the nature of the bonds in these - molecules and the reasons for the differences in the strengths, so we can say that Na_2 and Cl_2 has got > metallic bonding >
J: < metallic bonding <
T: and we can explain it 'cause, if they're in the same group, then
J: Mm.
T: they've got the same relative core charge, but the cæsium, > ~~atom~~ >

38 J: < But as you go down the group, < atomic radius increases.
39 T: Yeah, therefore explaining why the bond enthalpy also decreases, down the group.
40 J: So H_2 got equal sharing of electrons in the bonds,
T: yeah, we've got small molecule, > small atoms, ain't we? >
J: < So you've got < no polar, you haven't got any polarisation?
41 T: Erm?
42 J: What am I talking about? Talking rubbish.

……

43 T: Shall we just leave that one?
44 J: Yeah.

Appendix 26.

An example of editing Annie's case study.

In chapter 5 (§5.3) it was pointed out that Guba (1978) has suggested 'journalism' as an appropriate model for naturalistic research.

In preparing the case study of Annie, from the first cohort of colearners, I used a 'journalistic' approach to writing up the case. Having transcribed the interviews, and re-organised the data in terms of categories, I wrote up the case study to have a high level of readability by editing the evidence to give as far as possible a narrative form. (My interpretation of) Annie's thinking has been illustrated in her own words, but parts of utterances have been selected and spliced together to provide narrative, in the same way that a journalist might edit an interview for broadcast news.

As an example of the type of editing undertaken, consider the extract below from the case study of Annie. (The complete case study of the development of *Annie's understanding of chemical bonding during her A level course* was presented to a symposium at the 1993 Annual meeting of the British Educational Research Association. The extract is from section 5.2. Annie's case is discussed in chapter 7 of this thesis.)

> *The absence of evidence of bonding (by Annie's criteria) was compounded by confusion over the meaning of the plus and minus signs used to indicate positive and negative charges. The cations in fig. 5 were identified as sodium "atom"s (A1.250) despite the plus signs "representing the charges" (A1.246). The chloride anion was called a "chlorine atom" (A1.252). These errors could have been 'slips of the tongue', were Annie not consistent in confusing the meaning of the signs. This becomes apparent when she explains that the structure is held together by "the attraction from the plus to the minus because like chlorine's minus an electron and sodium is over an electron." (A1.260) For Annie the "plus and minus signs on them representing the charge" (A1.246) do not mean an overall electrical charge, but a deviation from noble gas electronic structures: "sodium has like one extra electron in its outer shell, and chlorine has seven electrons in its outer shell so it's minus an electron" (A1.262). What is given at G.C.S.E. level as the cause of electron transfer to form ions has become confused with the signification of the products of such a transfer: a '+' sign meant to indicate one less negative electron in*

> *the atom than positive charge in the nucleus is seen as meaning one more electron than a stable configuration. The formation of ions by electron transfer explains the origin of the electrostatic forces that hold an ionic lattice together. Annie's alternative conception of the '+' and '-' species means she must find an alternative mechanism to hold the substance together: "so by sort of exchanging, the sodium combining with the chlorine just by force pulls they would hold together" (A1.262). What does Annie mean by exchanging? "by, well just the attraction in them" (A1.264). From a conventional viewpoint Annie's conception of figure 5 makes little sense: the structure is held together, but without any bonding; there are charges on neutral atoms; atoms are combining without overlapping; and the atoms are exchanging not electrons but force pulls related to the electronic configuration. However Annie's comments seem to be more than just a make-shift argument put together on the spur of the moment. Indeed the misidentification of ions as neutral, although not entirely consistent throughout the interview, certainly pervaded Annie's comments. This misunderstanding was abetted by an interpretation of diagrams that only recognised bonding between species represented as circles (or similar) if there was overlap.*

The extract was written after due reflection on all four interviews, but the quotations are based on the following extract from the first interview,

A1

237 I: Any idea what that's meant to be? • • • • • • [pause, c.6s.]

238 A: Just sodium and chlorine atoms.

239 I: That's sodium and chlorine atoms, erm would you say that there was any kind of bonding there?

240 A: No.

241 I: No bonding. Why do you say that? What is the difference between that and the ones we've seen before?

242 A: Well the other ones electrons were shown, and these no electrons are shown and they don't actually overlap or anything they just go in rows.

243 I: They go in rows. Okay. Erm, so if you look at these, I mean you said they were sodium and chlorine

A: Yes.

I: because presumably you recognise the Na and the Cl,

A: Yeah.

I: but only two of them are labelled with 'Na' and 'Cl'.

244 A: Yes.

245 I: What about the others - what do you think they are?

246 A: They're probably sodium and chlorine, or else they could be, because of the signs, you've got plus and minus signs on them representing the charge, or else it could be similar elements going down the groups.

247 I: Okay so you recognise that these, these things represent charges, and you probably guess it's just me being lazy that I haven't labelled them all,

A: {laughs}

I: so I've just labelled the first couple, erm, so these are what, so you reckon this little one will be, what will that be do you reckon?

248 A: Sodium.

249 I: That will be a sodium, molecule?

250 A: Atom.

251 I: Sodium atom, what about this one here?

252 A: Chlorine atom.

253 I: That'll be an atom. But these have got charges on,

A: Yeah.

I: okay, but unlike [figures] 2, 3 and 4 we've seen previously they've had bonds in,

A: Yeah.

I: chemical bonds, whereas this, we don't have chemical bonds?

254 A: No.

255 I: Do you think this thing would fall apart? Or would it hold together?

•••••••••

256 A: If you heated it, or reacted it in some way, it would hold together, and it would probably get held together by just forces.

257 I: By forces. Any idea what kind of forces would hold it together?

258 A: Probably just the attraction.

259 I: Uh hm.

260 A: The attraction from the plus to the minus because like chlorine's minus an electron and sodium is over an electron. So they could just like hold them together, but not actually combine.

261 I: Right, chlorine's, so sodium's, say that about the electrons again.

262 A: Sodium has like one extra electron, 'cause it has like an extra electron in its outer shell,

I: Uh huh.

A: and chlorine has seven electrons in its outer shell so it's minus an electron so by sort of exchanging,

I: Huh hm.

A: the sodium combining with the chlorine just by force pulls they would hold together.

263 I: You say by exchanging, did you say?

264 A: Yeah by, well just the attraction in them.

Whilst reading interview extracts - such as the one just quoted - purveys a sense of discourse and dynamism that is necessarily lacking from the case study with its engineered narrative, it is the researcher's task to make sense of the colearner's comments, and to marshal the evidence in a way that supports the interpretation suggested, to provide the reader with an overview of the colearner's ideas that would not be gleaned from a single reading of the transcripts themselves. Close study of the primary data allows the researcher to juxtapose comments that were separated by many lines of text in the original transcripts, as in the following example taken from section 12.2 of Annie's case study:

> *By contrast, at the time of the second interview, Annie was certainly aware of the existence of van der Waals' forces, and knew they were relatively weak forces that were readily disrupted. Annie now reported that such forces occurred in iodine (figure 17), but she also suggested a wider range of examples. The atom (e.g. sodium, fig. 1) was held together by "van der Waals' forces ... weak forces, which pull towards the nucleus. Which are readily disrupted" (A2.2). In metallic iron (figure 6) "it's probably van der Waals' forces, holding it together" (A2.93), although these forces are not the same as metallic bonding "'cause you can get van der Waals' forces in, covalent things as well" (A2.107). Indeed lithium iodide (figure 8) is "ionically bonded, but the forces holding it together will be, (pause, 5s approx.) van der Waals' I suppose" (A2.125)."*

This extract uses data from the second interview, which I had construed as relevant to the category of *van der Waals' forces*. The citations show that the quotations are from utterances 2, 93, 107 and 125 of the transcript of that interview.

Appendix 27.

Preparing the case study of Tajinder.

§A27.0: An overview of the stages of producing the case study.

In this appendix I illustrate three of the stages in the preparation of Tajinder's case, intermediate between interviewing him, and writing the analysis that makes up chapter 8. Figure A27.1 gives an overview of the stages in preparing the case study (and further details may be found in chapter 5, §5.4).

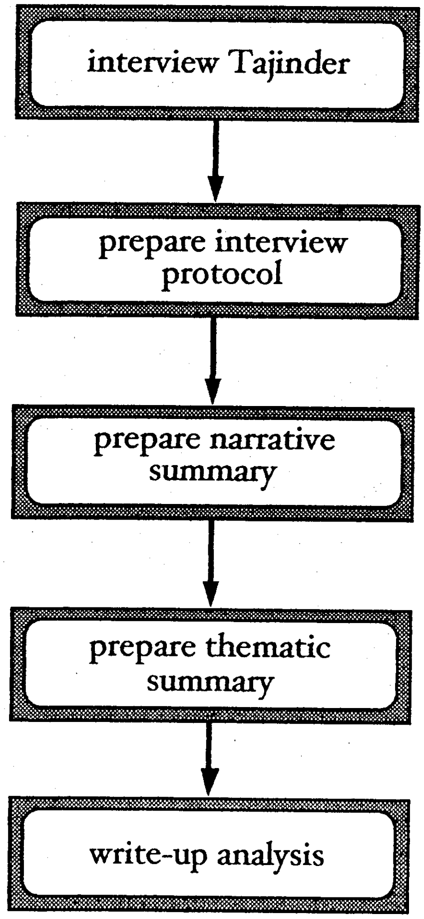
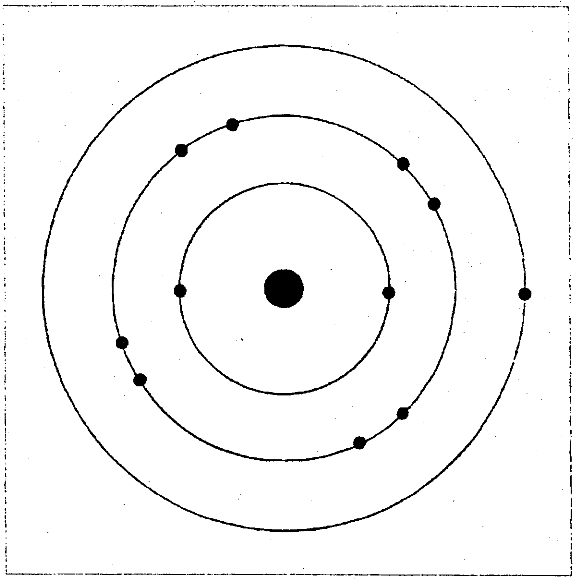


figure A27.1 stages in preparing Tajinder's case study

§A27.1: The interview transcript.

As an example consider interview T9, the last interview Tajinder gave before his first year examinations. The intermediate stages between the interview, and the final analysis are represented in the extracts on the following pages:

An interview protocol was prepared, including full transcription of parts of the interview of particular significance. The extract below is from the beginning of the interview (where Tajinder was asked about focal figure 1).



focal figure 1

T9.A029

I: Is that a stable, erm species, as shown there?

T: Erm, no.

I: Why not?

T: Erm, because it doesn't, erm, - a noble gas configuration.

I: Uh hm, so would it become stable somehow? Could it become stable?

T: If it became erm a sodium plus ion, if it lost an electron, then it'd become stable.

I: That'd be stable then would it?

T: Uh hm, yeah.

I: Is it able to lose an electron, become an Na^+ ion?

T: Yes.

I: How can it do that?

T: Erm, by donating it to a species that needs an electron to become stable.

I: Uh hm, so does it have to have something else next to it, or near it, in order to do that?

T: Erm, has to, has to give it away somehow, doesn't have to have, doesn't have to have the species that it gives it away to next to it.

T9.A047

I: So if I were to take that erm, sodium atom, and I were to take it into deep space, well away from any other materials, would it then donate its electron?

T: No, you'll have to give it energy to donate its electron.

I: Got to give it energy?

T: Yeah.

I: So erm, if I put some energy in then it would donate its electron?

T: Yeah.

I: Where would it donate it to?

• • •

T: Erm, if it was in space?

• •

T: To - don't - it wouldn't donate, it would just donate it, it would just take it - away.

I: Just lose it, would it?

T: Yeah.

I: Okay,

T9.A057

I: and what you're left with, would be what?

T Erm, one electron by itself and Na^+, ion.

I: And would that be stable?

T: More stable than it was, when it was Na.

I: Uh hm, what about the electrons, would the electron be stable by itself?

T: Not really, because [sic] you don't normally see like - electrons by themselves.

T9.A065

§A27.2: The narrative summary.

The interview protocol was used to prepare a 'narrative summary' of the interview. An extract is provided below:

T9.A004:
Interview took place on Tues. 22nd June 1993, the day before T's A1 examination.

T9.A012: fig.1 {sodium atom}
No chemical bonding was represented. The diagram showed one atom of sodium.
It was not a stable species, because it doesn't have a noble gas configuration. If it became a sodium plus ion, if it lost an electron, then it'd become stable. It can do that by donating it to a species that needs an electron to become stable. In deep space, well away from any other materials, you'll have to give it energy to donate its electron. It wouldn't donate, it would just take it away. You would be left with one electron by itself and Na^+*, ion. This would be more stable than it was, when it was Na. The electron would not really be stable by itself because [sic] you don't normally see electrons by themselves. You have to put energy in to remove the electron, because if you didn't have to put energy in to remove the electron, then solid Na wouldn't exist. If you needed no energy to remove the electron, then it wouldn't be there in the first place. (T decides this is a silly argument.) We need energy to remove it 'cause of the sodium nucleus, [which] has eleven protons which attract the electrons around it, and there's a certain amount of attraction between these two, there's an electrostatic force that holds the electrons around the sodium nucleus. The forces of attraction between the nucleus and this electron, and all the other inner electrons are equal. The force on the electron is towards the nucleus, it's pulling it in.*
There is a force on the nucleus due to this electron which is slight, really small, towards the electron. The force that acts on electron due to the nucleus is bigger than the force that acts on the nucleus because of the electron, eleven times bigger because this has got a charge of 1-, and this has got a charge of 11+.
There is a force of acting on an electron in the middle, it's the same force. Each electron has the same amount of force between the nucleus and itself, no one electron has more force to it than another. The nucleus doesn't attract that electron more than that electron, it attracts all electrons, like the same.
I asks 'would it be fair to say that the attraction is shared between them?', and T assents.

T9.A135:
The energy you need to remove the second electron is much higher, because it's harder to remove an electron from an ion than it is from an atom, because once once this electron is removed, the next electron that you have to remove is from a p orbital, which is at a higher energy, so you need more energy to remove the second electron, because the charge on the nucleus is still the

same, and there's one less electron to attract, so the nucleus has more attractions to these electrons, and because one electron has been taken away, there's less repulsion between all these electrons, so that the nucleus pulls the electrons in more, so the nucleus [sic, correct to atom, then ion, later] becomes smaller, the core, the charge is still the same, and [the overall charge?] becomes a plus, and the amount of energy to remove this one is greater than than one.

T9.A166:
I paraphrases T's 'conservation of force' argument: there's a certain amount of charge on this nucleus that's available to attract these electrons, so there's a force on these electrons, and that the force is shared out amongst eleven electrons, but if you were to remove this electron in some way, then there's only ten electrons left. And therefore the same amount of force, or whatever, is able to share amongst ten electrons, and therefore each of them's attracted more strongly than before.
T agreed he had said this, but he was not sure whether these electrons are more attracted because there is one less, and not because there's less repulsion between them. But they're more attracted, because it's certainly harder to remove the second electron than it is the first.

A27.3: The thematic summary.

The next step involved re-writing the material from narrative summary (which closely followed the order of the discourse in the original interview) thematically. Below is an extract:

The final interview of the first year with T ***(T9)*** *took place the afternoon before his end-of-year examination,* ***Tuesday 22nd June, 1993*** *(A103, 15.10 - 16.40). T was taken through some of the foci diagrams used in the first interview (T1).*

Bond: When asked how many bonds were shown in fig. 13 T became confused and unsure whether to count each bond from both ends (i.e. twice). T could not define a bond (he thought) but suggested it was a certain type of ***force*** *holding one piece of matter to another. When the word 'link' was suggested he had no difficulty counting up. T found it easier to count bonds when they were represented by electrons rather than lines(! - just familiarity?)*

In fig.16 the symbols intended to be ***dative bonds*** *are interpreted as* ***electrostatic forces****, due to the* ***attraction*** *from the aluminium nucleus for the chlorine electrons. This pull from the nucleus is like sort of a bond, well* ***not actually a bond*** *but it's like a force between them, which holds them together. I.e. this fits T's own definition of a bond (above) but is not a bond for him.*

Stability: the sodium atom was not stable because it did not have a ***noble gas configuration****. An isolated sodium ion and electron would be more stable. Hydrogen needs two electrons in its outer shell to get a* ***noble gas configuration****. Oxygen needs eight electrons to become stable.*

Different elements have different numbers of valence electrons, and they don't always ***want*** *to stay unstable, so they join up with other elements who also* ***want*** *to like share electrons. e.g. chlorine* ***needs*** *one electron to* ***think*** *it has a noble gas configuration.*

Lithium ***wants*** *two electrons in its outer shell to become stable, and it's easier for it to lose one than gain eight [sic], so therefore it* ***wants*** *to lose an electron. Iodine would* ***rather*** *gain one than lose seven. Ionisation: T's initial* ***argument to explain*** *why energy was needed to ionise an atom was* ***tautological****. The electron would not be stable by itself because you don't see them by themselves; energy was needed to ionise sodium because otherwise solid sodium would not exist. T seemed to confuse 'we know this because' with 'the reason for this is'.*

The second ionisation energy is higher because: the electron is removed from a ***p-orbital****, at a* ***higher*** *energy level, one electron has been removed and the nucleus has* ***more attraction*** *for the others (****conservation of force****), there is* ***less repulsion****, and the ion becomes smaller,* ***core charge is the same*** *[it has gone from +1 to +9], and [the species?] becomes a plus.*

The discussion above took place at the beginning of the session. It was revisited at the end (i.e. c.1 hour+ later.) T started to argue that the attraction on the second electron was the same whether the first electron was there or not, but because there was less repulsion between electrons the radius decreases and the distance between electron and nucleus was smaller, so it requires more energy to remove the second electron. Removing an electron changes the equilibrium, and the new equilibrium is at a smaller radius. (This did not seem to be referring to the shell! This argument would be valid considering the 2nd-3rd I.E.)

T then changed his mind again: there will always be a +11 charge on the nucleus, but when one electron is removed it ***only has to attract*** *ten electrons ('****conservation of force****'), so it has a certain amount of* ***greater attraction*** *for them, pulling them in closer. Another ionisation means only nine electrons to attract from 11+ charge. Eventually there would be 11+ charges attracting one minus charge so it would be really really hard to remove that electron.*

The ionisation energy would increase in a smooth line (surely a curve?) except there are certain ***hitches*** *- different* ***types of orbitals*** *and* ***spin-pairing*** *mean there's* ***jumps****.*

Appendix 28.

Tajinder's progression and new explanatory principles.

§A28.0: Tajinder's new explanatory principles.

In chapter 8 (§8.4.3) it was explained how at the start of his A level chemistry course Tajinder's thinking about chemical bonding was largely derived from his OCTET RULE EXPLANATORY PRINCIPLE. This explanatory principle was of limited utility in understanding chemical bonding to the depth required at A level. By the end of his course he had acquired two other explanatory principles which could be used to explain chemical bonds: the COULOMBIC FORCES EXPLANATORY PRINCIPLE, and the MINIMUM ENERGY EXPLANATORY PRINCIPLE.

§A28.1: Tajinder's progression is linked to adopting an electrostatic explanatory principle for thinking about chemical bonding.

Explanatory schemes based around the octet rule, although having an *origin* in CURRICULUM SCIENCE, may lead to explanations that are not valid scientifically. In both of the case of Annie, summarised in chapter 7, and of Tajinder, discussed in chapter 8, the development of understanding about chemical bonding was found to be related to the adoption of a complex of ideas based upon an electrostatic explanatory principle (§8.4.3). Tajinder adopted his COULOMBIC FORCES EXPLANATORY PRINCIPLE at an early stage of his studies, and was able to construct a more diverse associated complex during the A level course, than Annie.

The acquisition of an explanatory principle based on electrostatics enabled the student colearners to discuss aspects of bonding in ways that were not possible when they were restricted to using an explanatory principle based on the notion of full shells. So Annie's ELECTROSTATIC FORCES EXPLANATORY PRINCIPLE enabled her to explain the mechanism of covalent bond formation and the nature of hydrogen bonds, and Tajinder's COULOMBIC FORCES EXPLANATORY PRINCIPLE was used to accommodate new categories of bond: polar bonds, hydrogen bonds and van der

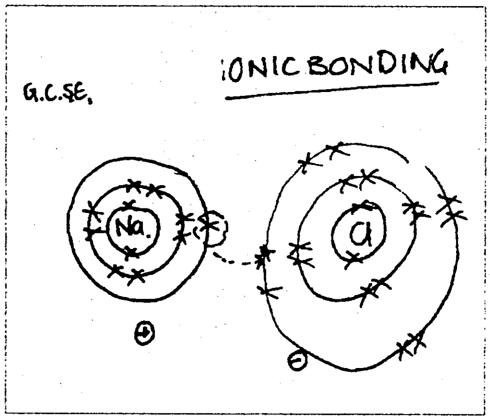
Waals' forces.

§A28.1.1: Tajinder's GCSE and A level models of the ionic bond.

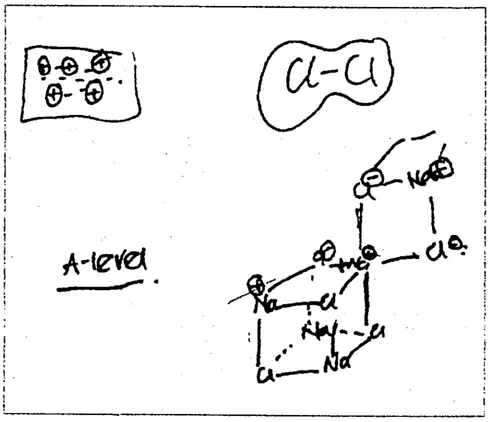
Tajinder's case is particularly interesting because he demonstrated an awareness of the plural nature of his bonding ideas, which suggests that he was able to conceptualise his own learning in something akin to 'toolbox' terms (see chapter 1, §1.7.2). An example of this that is particularly informative occurred at the end of his first year (interview T8). It is worth considering this example in depth as it illustrates how Tajinder was aware that he knew of two ways to explain the ionic bond, that he labels "G.C.S.E." and "A level". In terms of the present model Tajinder's "G.C.S.E." explanations were based upon his OCTET RULE EXPLANATORY PRINCIPLE, and his "A level" explanations upon his COULOMBIC FORCES EXPLANATORY PRINCIPLE. At this point in his course Tajinder has considerable competence in using the former principle, but is now aware from his A level work that it has shortcomings. However, he has not yet come fully to terms with the more advanced approach. In the interview Tajinder may be found to struggle to find a bridge between the two complexes (c.f. the model in chapter 2, §2.10.3, fig.2.2). He was asked to draw and explain the different types of bond he had studied during the year. Tajinder suggests ionic bonding, but is aware that although he has learnt a model of this prior to A level studies, it is not always acceptable at A level,

> "Ionic bonding is, ***in simplistic terms*** when you have two atoms, they come come together and erm, say sodium and chlorine, and chlorine has got 7 outer electrons and ***needs*** another electron to have a ***noble gas configuration***, and sodium has one outer electron and it ***needs*** to lose that electron to also gain a ***noble gas configuration***, and as erm, sodium ***gives*** it to chlorine, they erm, that's ionic bonding ***in simplistic terms***."
> T8.A067

Tajinder repeats that this explanation is 'in simplistic terms'. It is an explanation based on his OCTET RULE EXPLANATORY PRINCIPLE, with atoms 'needing' noble gas configurations. When setting out to represent ionic bonding in a diagram Tajinder comments "this is what we do in G.C.S.E. and I'll draw on what we do at A level as well" (T8.A092).



Tajinder's diagram of ionic bonding, June 1993
detail- "G.C.S.E."



Tajinder's diagram of ionic bonding, June 1993
detail - "A level"

As he draws Tajinder discusses his diagram. He explains that,

> "...in ionic bonding bonding the ... outermost electron on the sodium atom is erm given away to the chlorine atom, and it receives that one, and, then they have type of bond - this ionic bonding which [is the] transfer of electrons, from sodium to chlorine. And ... because it's lost an electron it becomes positive ion, and this becomes a negative ion, and there's a force between positive and negative which attracts them. But in ... A level ... ionic bonding ... never takes place just between ... one atom and another atom - we can't separate an atom and an atom and combine them together. So ... if we made erm sodium chloride in the lab, we would have erm sodium metal and we'd have chlorine gas. And sodium metal ... exists in metallic bonding because ... it's a metal and it doesn't go round by itself - and it forms onto other sodiums and you have a piece of sodium with electrons, delocalised electrons around. And you have erm chlorine gas which goes around in two - in in a molecule - and erm you combine these two together - and you form a structure, a solid structure which ... doesn't consist of just two atoms, it consists of hundreds of millions of atoms, joined together. And ... in ionic bonding, because there's so many ... sodium and so many chlorine, you can't tell which ... sodium gave which chlorine it's electron. So ... there's no way of recognising which sodium belongs to which chlorine, and each of the bonds, between each sodium and each chlorine is equal to one another. So not one sodium or chlorine has a stronger bond to each other than say another sodium or chlorine."
> T8.A109

This extract demonstrates that Tajinder is attempting to move beyond the familiar "G.C.S.E." (i.e. OCTET RULE EXPLANATORY PRINCIPLE) model of ionic bonding, to explain the bond in "A level" terms. He is clear that representations of ionic bonding presenting a single electron transfer event between a single atom of a metallic element and a single atom of a non-metallic element, to give an ion pair, do *not* represent a chemically meaningful system. However he does not delve into the mechanism of how and why the existing bonds in metallic sodium and molecular chlorine may be broken. Tajinder also emphasises that "each of the bonds, between each sodium and each chlorine is equal to one another. So not one sodium or chlorine has a stronger bond to each other than say another sodium or chlorine", which represents a significant step away from the OCTET RULE EXPLANATORY PRINCIPLE interpretation he had used earlier in the course; however Tajinder's justification is couched in the language of this familiar complex: "there's so many ... sodium and so many chlorine, you can't tell which ... sodium *gave* which chlorine it's electron. So ... there's no way of recognising which sodium ***belongs*** to which chlorine". This way of talking might seem a vestige of a scheme now abandoned in view of Tajinder's statement that "there's a force between positive and negative which attracts them".

However later in the interview, the discussion returned to Tajinder's diagram of ionic sodium chloride, and it becomes clear that the COULOMBIC FORCES EXPLANATORY PRINCIPLE does not explain the bond satisfactorily for Tajinder. Instead he tries to accommodate his A level knowledge that ions bond with all their neighbours, with the notions that the ionic bond is due to electron transfer, and the number of bonds is limited by the number of electrons transferred,

I: Right, okay. So how many bonds does each sodium have?
T: Erm.
•••••• [pause, c.6s]
T: Just one.
I: Right can you so, if I took say this sodium here,
T: Uh hm.
I: Whereabouts is its bond?
T: Oh it's, it's not actually erm
••
T: because sodium, sodium can lose one electron, and that you would think that it could represent one bond, but erm in this case the sodium can lose one electron, but erm, that electron doesn't necessarily go to that chlorine, it can move around.
I: The electron can move around? ... Sorry I wasn't sure what was moving around there [T]?
T: Mm. {laughs} - No the bond can move around, the bond can move around from each chlorine.
T8.A391

Tajinder was not able to explain this any further on this occasion. The notion of each sodium atom forming one ionic bond that moves around may be interpreted as a tentative attempt on Tajinder's part to bridge between two explanatory schemes: the OCTET RULE EXPLANATORY PRINCIPLE only allows sodium one bond, but the COULOMBIC FORCES EXPLANATORY PRINCIPLE requires equal bonding with all neighbouring counter ions, and a mobile bond could satisfy both requirements. However the mobile ionic bond also fails to fit with key elements of both schemes, the tie-in with the electron transfer event in the OCTET RULE EXPLANATORY COMPLEX, and the attractions between opposite charges (which are permanent) in the COULOMBIC FORCES EXPLANATORY COMPLEX.

Later in the interview, our discussion returned again to the same theme. Tajinder began to explain ionic bonding in terms of the OCTET RULE EXPLANATORY PRINCIPLE, but then has a pause for thought, and mumbles *sotto voce* that he thinks he's found the right explanation, before putting a *caveat* that he was talking "in simplistic terms", and again implying that something is moving around,

I: And what is an ionic bond?
T: Erm.
••••• [pause, c.5s]
T: Erm, ionic bond?
•••••
T: It's where, erm an atom either loses or gains an electron to enable it to have a noble gas configuration.
...
I: Then why do we draw the bond between two ions, if an ionic bond is when an atom loses or gains an electron?
...
[Then after a pause for thought]
T: This, what I said before, I think, erm,
•••
T: when this sodium, sodium has got one outer electron that it wants to lose, to gain a full, to gain noble gas configuration, 'cause it's got one er, one electron in this outer shell, outermost shell. Yes?
I: Uh hm, yeah.
T: And erm,
••
T: the chlorine needs to gain an electron to have a ... noble gas configuration, and ... if I drew this structure out, they'd be the same number of sodiums as chlorines, so it's a ratio of 1:1,
I: Uh hm?
T: so therefore, erm, each chlorine atom
•••
T: would have
••••••••••
T: (erm)
••••
T: (I think that's right.) Is it because erm, when you have that type of bond where, in simplistic terms, this doesn't, this electron on sodium doesn't mean necessarily that it's going to stay with this chlorine. It's able to move around, so it can go, and it can go and join with another chlorine and it forms equal amount of bonds, so equal strength.
T8.A442

Rather than the bond moving around, Tajinder here seems to be suggesting that it is the donated electron that moves around between chloride ions. However when an attempt is made to recapitulate, and the suggestion is put to him, Tajinder decides that this is not right.

I: Let's see if I've got this, if I've got this right. Are you saying that in, in this structure,
T: Uh hm.
I: that this sodium ion has lost an electron,
T: Yeah.
I: or donated an electron. And maybe this chlorine acquired that electron?
T: Yeah.
I: But that this extra electron could leave this chloride ion and maybe move to this one instead?
T: Erm. No, no, no {laughing}.
T8.A471

There then follows another period of thought before Tajinder has another attempt to produce an explanation of ionic bonding that he is satisfied with. This time he uses his COULOMBIC FORCES EXPLANATORY PRINCIPLE, and focuses on the consequences of the ions being charged,

> "is it because erm, sodium has formed positive ions, and chlorine formed negative ions 'cause they've gained an electron, and... sodium has lost an electron, and ... it's not erm clear which erm chlorine the sodium donates its electron to, but because this is negative and this is positive, there's a certain amount of attraction between them and therefore, • this is why there's a bond, electrostatic, er, dunno."
> T8.A480

At this point Tajinder *has* explained the bond in terms of the COULOMBIC FORCES EXPLANATORY PRINCIPLE, and this explanation - "there's a certain amount of attraction between them" "because this is negative and this is positive, and therefore ... there's a bond, electrostatic" - is satisfactory from a CURRICULUM SCIENCE viewpoint. However Tajinder's own evaluation of his response shows he is less convinced, as he "dunno". Although Tajinder has developed a COULOMBIC FORCES EXPLANATORY COMPLEX, and by this stage of his course he has demonstrated he can apply it in a range of contexts, *he* is not satisfied describing ionic bonds purely in terms of electrostatic forces. Tajinder seems to seek an explanation that is in keeping with his OCTET RULE EXPLANATORY PRINCIPLE, or what he refers to as "what we do in G.C.S.E.", even though he knows that such an explanation is "in simplistic terms".

§A28.1.2: Tajinder applies octet thinking to precipitation.

At this point in the interview I decided to move the discussion in a direction that was intended to lead to Tajinder realising the advantages of the electrostatic perspective. The 'scaffold' (c.f. chapter 2, §2.23) I provided was in the context of precipitation or double decomposition reactions, and, as mentioned in chapter 8 (§8.4.5), in particular:

barium nitrate soln.. + sodium sulphate soln.. → sodium nitrate soln.. + barium sulphate ↓

Tajinder described the bonding in both of the reactants, and also the bonding in the precipitate, as ionic. He explained the ionic charges in sodium sulphate in terms of electron transfer from sodium to sulphate; and in barium nitrate the charges were due to electron transfer from barium to nitrate (T8.B139). He was able to draw solutions of these reagents showing the ions dissociated. He knew that on mixing a precipitate of barium sulphate would be formed.

This context was *intended* to lead Tajinder to the conclusion that in the precipitate it was meaningless to consider the ionic bond in terms of electron transfer, as the barium ions had (according to his own statements) donated electrons to species not present in the lattice (nitrate ions which were still in solution), and the sulphate ions had accepted electrons from species not present in the lattice (sodium ions which were still in solution). In this context the ionic bonding would make sense from the COULOMBIC FORCES EXPLANATORY PRINCIPLE, but not from the OCTET RULE EXPLANATORY PRINCIPLE. However, Tajinder put a different interpretation on this 'double decomposition' process,

I: And then when we go to barium sulphate,
T: Uh hm.
I: the '2+' tells us?
T: It's lost two electrons, er it's, it's lost two electrons, yeah.
I: And the er, '2-' on the sulphate tells us?
T: It's gained two electrons.
I: And where has the barium lost two electrons to?
T: The sulphate?
I: And where has the sulphate gained two electrons from?
T: The barium.
T8.B162

So here Tajinder suggests that electron transfer occurred between barium and sulphate to form ions, which seems to contradict what he had previously stated (that the barium ions were formed when electrons were transferred ***to nitrate***, and that the sulphate ions were formed when electrons had been transferred ***from sodium***). Tajinder explained that he was assuming that when the two solutions were mixed any cation present would "take its electrons back and to give them away wherever they are, to form their atoms again" (T8.B250). From a CURRICULUM SCIENCE perspective, such reinstatement of electrons to their original atoms was not only unnecessary to explain the bonding in the precipitate, but would also lack any physical cause. However, within Tajinder's thinking, ionic bonding was closely linked to electron transfer events, and thus it was necessary to 'discharge' the ions in solution so that new electron transfer events could occur, to form new ionic bonds.

When Tajinder was probed about the reasoning behind his scheme, he was unable to suggest a reason ***why*** electrons would be transferred back to their original atoms, and (apparently a more potent argument from his perspective) doubted there was time for the electrons to be reinstated on mixing. So he then accepted that ions would be present in the mixture, and barium and sulphate ions would "react together" giving the precipitate (T8.B285).

At this point then Tajinder had accepted that the precipitate had formed from ions that were already charged before they interacted to form barium sulphate, and logically there is no justification for explaining the ionic bond in barium sulphate in terms of electron transfer. However, it might be said that Tajinder had a 'habit of mind' of using his OCTET RULE EXPLANATORY PRINCIPLE,

I: Is there any kind of bonding, here?
T: Ionic.
...
I: Why is this barium two plus?
T: Because it's lost two electrons.
I: Why is this sulphate two minus.
T: Because it's gained two electrons.
I: Well where did the two electrons go from, from this barium two plus?
...
T: To sulphate ions.
I: And where did the two electrons come from on this sulphate ion?
T: Barium ions.
I: Would you like to think about that?
[Pause of approximately 24s whilst Tajinder re-considered.]
T: For barium to become a two plus, has lost electrons, to sulphate ions.
I: You're happy with that?
• •
I: Does that make sense to you?
T: Mm.
T8.B397

Only when the discrepancy was made explicit did Tajinder realise that his explanation in terms of the OCTET RULE EXPLANATORY PRINCIPLE did not make sense,

I: The only reason I'm not very happy with that is that ... when I asked you ... why this barium was two plus,
T: Uh hm
I: you told me it had lost two electrons to nitrate groups.
T: Uh hm.
I: And when I [asked you] why this sulphate was two minus, you told me it had gained electrons from sodiums.
T: Mm.
I: And then we put them in solution here, and you still told me this sulphate had got its electrons from the sodiums. And that this barium had given its electrons to nitrates. And then we mixed them up, and you claimed that they were neutral, but then you changed your mind and decided that they didn't have time to be neutral, and that when you mixed them together, they would be ionic.
T: Mm.
I: <u>This</u> barium two plus,
T: Oh yeah!
I: was that not the barium two plus
T: {tut}
I: over there before?
T: Oh yeah.
I: This sulphate two minus, didn't it come from this [test] tube here?
T: Yeah.
I: And when we mixed them together, we formed, this diagram.
T: Uh hm.
I: So are you, are you suggesting that - maybe this sulphate gave its two electrons back to sodium atoms, and than ran off to find a barium to get two new ones from?
T: {laughing} No.
I: When I put it like that it sounds silly doesn't it?
T: Yeah.
I: But that's almost what you said earlier about "... had it had time to give its electrons back?"
T: Oh yeah. So it hasn't had time had it?
T8.B416

Even at this point Tajinder does not question his scheme from an electrostatic viewpoint - that is, that there is no a priori reason why the ions should return the electrons (as electrons donated to or accepted from one particular source are no different to any others), nor that there is any mechanism by which such a reinstatement is likely. Rather, Tajinder accepts that the ions have their original electrons because they have ***not had time*** to exchange them. However, Tajinder ***is*** now convinced that his original scheme has shortcomings, and is able to revisit the hypothetical barium sulphate precipitate in the light of the discussion, and then to apply the same perspective to sodium chloride,

I: So why do these ions here stick together. Why don't they just fall apart?
T: Because erm, the barium has lost two electrons so it's got an overall charge of plus two, making it positive. And the sulphur has gained two electrons making it overall charge of two minus, and positive and negative attract, that's why it forms a type of bond.
...
I: So if we go back to you picture of sodium chloride,
T: Uh hm.
I: where are there ionic bonds in that diagram?
• • • • [pause, c.4s]
T: Everywhere.
I: So how many ionic bonds does each sodium have?
T: Erm.
•
T: (One, one two three - erm - two three four -) six.
I: Six?
T: Yeah.
I: And do those bonds move about?
T: No.
I: And do these electrons move about?
T: No.
I: No? Are those bonds equal?
T: Yes.
I: Is any of those bonds of a chlorine, who got its extra electron from a sodium.
T: Don't know.
...
I: Okay, how do you feel?
T: Oh, much more intelligent.
T8.B454

§A28.1.3: Tajinder demonstrates progression.

Tajinder was next interviewed two weeks later, and when figure 5 was shown, Tajinder was able to use his new interpretation of the bonding,

I: ... this is diagram number 5, I wonder if there's any bonding present in figure 5.
T: Erm
• • • [pause, c.3s]
T: ionic bonding, present.
...
I: Right, so what's ionic bonding in terms of this diagram?
T: Er, in terms of this diagram, it's where you have like a lattice arrangement of positive and negative charges, like next to each other, in, in a certain type of arrangement.
I: Right, okay. Erm, are there any ionic bonds there then if this is ionic bonding?
T: Erm, yeah.
I: So where are the ionic bonds?
T: Erm, between each positive, ... this only shows like erm, do you know, you have like a building, like stories, this is just like cut straight through,
I: Uh hm?
T: so you can only see two-dimensionally. ... But then ...below one of the positive charges there would be a negative charge underneath it, [and] there would be one above it. So there would be like ... six bonds, to that one plus ion.
I: So each plus ion has six bonds, does it?
T: Yeah, > six nearest neighbours. >
I: < What about the negative < ions?
T: They would also have six positive > ones. >
I: < So they would have < Would they have
T: Yeah.
I: six ionic bonds as well?
T: Yeah.
T9.A381

So in this context Tajinder appeared to have progressed from using his OCTET RULE EXPLANATORY PRINCIPLE to applying his COULOMBIC FORCES EXPLANATORY PRINCIPLE.

§A28.1.4: Tajinder considers atomic stability.

In the same interview Tajinder had also discussed several diagrams showing molecules, and shortly after this point in the interview he was asked to explain why different atoms tend to form different numbers of bonds. His response was in terms of his OCTET RULE EXPLANATORY PRINCIPLE, which is not in itself inappropriate in the sense that explaining valency is the main purpose of the octet rule. However, Tajinder's OCTET RULE EXPLANATORY COMPLEX extends the octet rule, a guide to which electronic structures are commonly found in stable materials, to become a ***mechanism*** in terms of atoms that behave as active agents, so atoms "don't always ***want*** to stay ... unstable, so they join up with other elements who also ***want*** to ... share electrons" and chlorine "***needs*** one electron to ... ***think*** it [has] a noble gas configuration",

I: So why do these different atoms have different numbers of bonds?
T: Because when you find them in their atom state, erm, they they have a certain amount of a certain number of electrons, and erm, that's not always stable, that's why you get differing compound, differing elements, depending how many electrons they have in their valent shell, and they don't always want to stay, like unstable, so they join up with other elements who also want to like share electrons. If we're considering [focal figure] number 3, er like erm, because chlorine has seven outer electrons it needs one electron to become, like have a noble gas configur¬ or thinks it, have a noble gas configuration. So four chlorines would join onto one carbon, to become stable.
I: So chlorine's got seven electrons?
T: In its outer shell.
I: And, and that's not a stable situation, seven electrons?
T: No.
I: So what would be the stable situation?
T: Eight electrons.
T9.A401

It is interesting to note that Tajinder's reference to finding materials in their unstable "atom state" does not relate to his own experience of chemistry where he would have had no direct experience of materials in the form of discrete atoms. Rather such an 'atomic state' is conjectured in such thought experiments as the Born-Häber cycle (where reactions are analysed as if a sequence of discrete steps). However, the tendency to consider discrete atoms as the starting point for discussing chemistry was found in other learners, and is illustrated in chapter 11 (§11.1). Tajinder's treatment of a precipitate (discussed above) as though it derived from neutral species, even though it was known to have been prepared from ions, may be part of this same tendency: i.e. considering how barium ions in the precipitate came to be charged rather than neutral atoms, even though at the start of the thought experiment barium was already present as ions.

Tajinder was able to apply a similar analysis to a number of other examples, including sodium,

I: An if we went back to diagram number 1, which was sodium.
T: Uh hm.
I: How many electrons does that have?
T: Er, one.
I: So is that not stable?
T: No.
I: So, what does that have to do then?
T: Lose an electron.
I: So how many bonds does that form?
T: One.
T9.A428

Tajinder had explained that sodium and chlorine each form one bond, and this set the context to discover whether Tajinder could explain how sodium and chlorine could form six [ionic] bonds in NaCl, although they only form one bond each according to his OCTET RULE EXPLANATORY PRINCIPLE,

I: Right okay, and how many bonds did you say there were in this diagram number five?
T: Erm, six.
I: Six for each?
T: Six for each.
...
I: Six for each sodium, six for each chlorine?
T: Yeah.
I: And yet you just told me that erm sodium forms one bond and chlorine forms one bond?
T: Mm.
T9.A428

Tajinder was asked if he wished to comment on this apparent discrepancy,

> "this is because, when you get sodium metal and you get chlorine gas and you react them together, ... you have to give them energy to react. And when you give them energy they break up into ... the sodium plus and the chlorine minus ... ions .... But the sodium has to lose an electron to something, and it gives it to chlorine, but ***it doesn't know*** which chlorine it gives it to, so once this sodium has ... lost its electron ***it doesn't really care*** where it goes to, and ... similar with the chlorine, when it gains an electron ***it doesn't care*** where it ... came from, and erm, therefore it has no attachment to one single sodium, ... but because there's positive and negative charges and electrostatic forces bringing them together, they form into a type of ionic structure, positive negative positive negative, and ... to the positive there's, there can be six nearest negatives, in an arrangement. And so it looks like there's six, so there are six bonds between them, but because the sodium has lost an electron and the chlorine has gained one, it doesn't mean that the chlorine next to it has gained an electron from the sodium, it could have gained it from the one other there, but it doesn't matter."
> T9.A428

Here Tajinder is able to explain the bonding in the lattice in electrostatic terms: "because there's positive and negative charges and electrostatic forces bringing them together, they form into a type of ionic structure, positive negative positive negative, and ... to the positive there's, there can be six nearest negatives, in an arrangement". Tajinder starts to explain why "it ***looks like*** there's six" bonds, and corrects this to "there ***are*** six bonds between them". He emphasises that the electron transfer history is not significant to the bond, "it doesn't matter" whether "the chlorine next to it has gained an electron from the sodium", a point that is important in establishing how his thinking has progressed from earlier interviews. (It will be noted however that part of Tajinder's justification of the equal bonds is in the anthropomorphic terms that the ions concerned do not "know" or "care" about the history of the electron transfer events.)

Another example of Tajinder moving between complexes based in different explanatory principles occurs earlier in the same interview. In the following extract the dialogue moves through four stages. In the first stage Tajinder explains how the sodium atom is unstable (which is true from the OCTET RULE EXPLANATORY PRINCIPLE, but not *necessarily* from the COULOMBIC FORCES EXPLANATORY PRINCIPLE),

I: Is that [focal figure 1, a sodium atom] a stable, erm species, as shown there
T: Erm, no.
I: Why not?
T: Erm, because it doesn't, erm, a noble gas configuration.
I: Uh hm, so would it become stable somehow? Could it become stable?
T: If it became erm a sodium plus ion, if it lost an electron, then it'd become stable.
I: That'd be stable then would it?
T: Uh hm, yeah.
I: Is it able to lose an electron, become an Na$^+$ ion?
T: Yes.
I: How can it do that?
T: Erm, by donating it to a species that needs an electron to become stable.
I: Uh hm, so does it have to have something else next to it, or near it, in order to do that?
T: Erm, has to, has to give it away somehow, doesn't have to have, doesn't have to have the species that it gives it away to next to it.
T9.A029

From his OCTET RULE EXPLANATORY PRINCIPLE a sodium atom will always be unstable, where from an electrostatic perspective one would need to consider the overall system: if there was a species exerting a greater pull on the electron (perhaps in Tajinder's terms "a species that needs an electron" more) transfer would occur. From the viewpoint of the COULOMBIC FORCES EXPLANATORY PRINCIPLE however, the neutral atom would be more stable than the separated cation and electron. From a CURRICULUM SCIENCE perspective, another way of saying this would be that energy is needed to separate the electron from the rest of the atom. Tajinder made this point as the dialogue continues,

I: So if I were to take that erm, sodium atom, and I were to take it into deep space, well away from any other materials, would it then donate its electron?
T: No, you'll have to give it energy to donate its electron.
I: Got to give it energy?
T: Yeah.
I: So erm, if I put some energy in then it would donate its electron.
T: Yeah.
I: Where would it donate it to?
• • •
T: Erm, if it was in space?
• •
T: To, don't, it wouldn't donate, it would just donate it, it would just take it away.
I: Just lose it, would it?
T: Yeah.
I: Okay, and what you're left with, would be what?
T Erm, one electron by itself and Na$^+$, ion.
I: And would that be stable?
T: More stable than it was, when it was Na.
T9.A047

Here Tajinder does not seem to equate energy level of the system with stability,

I: Why do you have to put energy in to remove the electron, > if it's not stable? >
T: < Because - < erm
• • • • • • • [pause c.7s]
T: hm
• • •
T: because erm - if you didn't have to put energy in to remove the electron, then Na, Na, solid, Na, wouldn't exist, would it?
I: Explain that to me.
T: Erm. If you're asking, why do you need a certain amount of energy to remove the electron, if you needed no energy to remove the electron, then it wouldn't be there in the first place....
T9.A065

Here Tajinder's argument takes the form that if energy was not needed to remove the electron, then the electrons would leave spontaneously, and sodium would not exist as a solid metal. Therefore, from this logic, as sodium does exist as a solid metal Tajinder knows that energy is needed to ionise sodium. Leaving aside a flaw in this argument that does not substantially change its logical form (*i.e.* that removing an electron from sodium ***metal*** is not equivalent to removing an electron from a sodium atom), Tajinder's argument seems circular - things are the way they are because that is the way they are. Perhaps a more appropriate interpretation is that Tajinder was not answering the question '***why*** do you have to put energy in to remove the electron', but rather an alternative question '***how do you know that*** you have to put energy in to remove the electron'. (There were several occasions in the case study when Tajinder appeared to answer the question how he ***knew*** something to be so, rather than why it *was* so. For example in the eleventh interview he reports that van der Waals' forces are weak ***because*** a little bit of energy will separate the molecules; and that ethanol has a high vapour pressure ***because*** it has a lower boiling temperature.) Tajinder makes another attempt to put this argument, but then recognises it does not satisfactorily answer the question (he evaluates his suggestion as "that's silly"), by which time he has been able to switch to a response from his COULOMBIC FORCES EXPLANATORY PRINCIPLE,

T: How can I explain? Say er we have to apply a certain amount of energy, to remove this electron.
I: Mm.
T: We have to apply that energy to remove the electron, oh no that's silly. Did you ask why we needed energy to remove it? We need energy to remove it 'cause of this, the sodium nucleus, has (two eight) eleven protons which attract the electrons around it, and there's a certain amount of attraction between these two, there's a force, an electrostatic force that holds the electrons around the sodium - nucleus.
T9.A079

Despite this use of electrostatic ideas to explain why the electron is bound to the atom, Tajinder later reiterates that a sodium atom is unstable, and has to "lose an electron" (T9.A428). At this point in his development the term 'stable' seems to be used in terms of the OCTET RULE EXPLANATORY PRINCIPLE, and not to be strongly associated with electrostatic notions. Another example occurred when Tajinder was discussing the bonding between the $AlCl_3$ units in aluminium chloride, early in the second year of the course. Tajinder had explained that the dimer would hold together because of a "gap" in the electron density so that the nucleus is "exposed" and there is an attraction with the chlorine. However alongside this electrostatic argument is an explanation of why this attraction qualifies as a bond - because the aluminium atom is able to "think" it has eight outer electrons, and is therefore stable,

> "there's a force of, there's attraction between the two, which holds them together. And ... if you draw the electron density, around it, there's a sort of a gap over here, because there's no electrons present there. And what happens is ... because ... there's a gap over here, ... the nucleus positive part is like, exposed, and the chlorine comes and attacks it, *tries* to attract to it, or the erm aluminium attracts the chlorine, so there is a type of erm bond there, ... because erm, when this happens the aluminium *thinks* that it's stable because it's got eight outer electrons, but really it hasn't, but it *thinks* that it has, I think."
> T10.A524

§A28.2: Tajinder's progression is linked to adopting physical causes for bond formation.

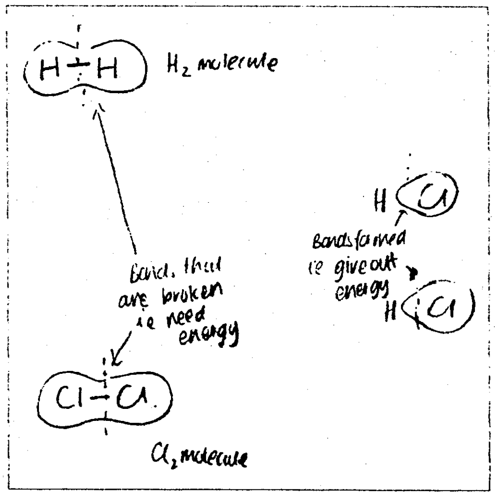
Although Tajinder develops a COULOMBIC FORCES EXPLANATORY PRINCIPLE to explain bonding, he also develops an apparently independent complex of ideas for explaining why chemical processes occur, based on the MINIMUM ENERGY EXPLANATORY PRINCIPLE However, as with the COULOMBIC FORCES EXPLANATORY PRINCIPLE, Tajinder is only slowly able to substitute this for elements of his preexisting OCTET RULE EXPLANATORY PRINCIPLE.

§A28.2.1: Tajinder's explanation of the reaction between hydrogen and chlorine.

During the eleventh interview Tajinder explains that hydrogen and chlorine will react. Tajinder had drawn a representation of a hydrogen molecule and a chlorine molecule. The discussion takes place after a consideration of the energy changes that occur when mixtures are formed, and is introduced through a context focussing on a theme of energy,

> I: Is it possible they would react together?
> T: Yes.
> I: Spontaneously, or would you have to put some energy in?
> T: E:r:m, I think you have to give off a - spark and they'll react.
> I: Uh-huh. Will we get the energy back if we did that?
> T: Yes.
> I: Okay.
> T11.B435

Tajinder next drew the product, molecular hydrogen chloride, and was then asked why hydrogen and chlorine should react to give hydrogen chloride.



Tajinder's diagram for the formation of hydrogen chloride , October 1993

Tajinder's reason was that there was "more energy given out than is taken in",

I: So why does that reaction occur?
T: ...because the amount of energy, there's more energy given out than is taken in.
I: Why is energy taken in?
T: To break bonds.
I: Why is energy given out?
T: When bonds are formed.

...

I: So you think more energy is given out making those two hydrogen chloride bonds, than [is used] breaking the chlorine bond and the hydrogen bond?
T: Yeah.
I: And that explains why that reaction occurs.
T: Uh hm.
I: So, didn't you have to put energy in though?
T: We did.
I: But that was okay, was it?
T: It was just a little spark.
I: It was just a little spark. But it was okay putting energy in, because?
T: Yeah. Because the amount of energy - was given out, ... how can you say it, counteract, the amount of given in.
I: Yeah, more than compensated for it.
T: 'More than compensated', that's right.
T11.B454

In the extract above there is evidence that Tajinder seems quite comfortable explaining chemical process in terms of an overall decrease in energy level. However, later in the same interview, Tajinder is once again asked "why there should be a reaction between this hydrogen molecule and this chlorine molecule?" His reply is now based on a different axiom, the OCTET RULE EXPLANATORY PRINCIPLE,

> "They *want* to gain a noble gas configuration, or ... stable erm outer shells, and as this, as hydrogen has got an electron which it can get rid of, and the chlorine has got er a shell where it can accept an electron, they'll both combine forming an ionic bond, where erm, electrons, where the hydrogen electron is taken by the chlorine.
> T11.C461

Not only does Tajinder not seem to bring his MINIMUM ENERGY EXPLANATORY PRINCIPLE to mind at this point, but he classes the bond as ionic rather than polar (an example of his octet thinking cuing a dichotomous classification of bond type, as discussed in chapter 11) and seems totally unaware that the argument he puts forward is invalidated by the figure being discussed - one he himself had drawn earlier. Even when he is questioned about his diagram he seem oblivious to this point,

> I: So in the diagrams they haven't got full outer shells, on the left hand side?
> T: No.
> I: But they have on the right hand side?
> T: Yeah.
> T11.C472

It would seem that the OCTET RULE EXPLANATORY PRINCIPLE was so well established as a rationale for bonding that Tajinder gave responses that were contradicted by the diagram that he himself had drawn earlier in the same interview (which showed the hydrogen and chlorine to be molecular *before* the reaction). Tajinder was asked again, with emphasis put on the molecular nature of the species shown, and he then realised that the electronic configurations had not changed. At this point he searched for an alternative rationale for the reaction, but the argument about energy changes used earlier did not come to mind,

> I: On the left hand side,
> T: Uh huh.
> I: in the hydrogen molecule, *that's actually a hydrogen molecule*.
> T: Yeah.
> I: How many electrons in the hydrogen outer shell?
> • • • [pause, c.3s]
> T: Hydrogen outer - that would be ... two.
> I: What about in the chlorine outer shell?
> T: Erm. There's - eight.
> I: So why react then, if they've already got full outer shells?
> T: Because
> • • • • • • • • • • • • • •
> T: oh, is it 'cause to do (oh actually). Is it because to do with the electron density, erm, both the chlorines have got erm, the same amount of electron density around each chlorine, and what it *wants* really to gain is to gain more - gain all, more of the electrons to itself, whilst the hydrogen doesn't, it is *not really bothered*. No, that's not really very good is it!
> [both laugh]
> T: So the chlorine er reacts with the hydrogen so therefore it can pull in more electrons towards itself, and therefore *feel* stable - *feel* more stable.
> • • •
> T: I don't know the answer to that question.
> T11.C479

Tajinder's abandoned argument uses the concept of electron density, and Tajinder seems to understand that in the hydrogen chloride molecule the electron density around a chlorine centre will be higher than it was in the Cl_2 molecule. Tajinder had previously demonstrated that by this stage he had available concepts related to the COULOMBIC FORCE EXPLANATORY PRINCIPLE - electronegativity and core charge - that could have been applied to develop the 'electron density' argument. However, Tajinder continues to use the language of the OCTET RULE EXPLANATORY PRINCIPLE, so that chlorine atoms "*want* ... more of the electrons" "whilst the hydrogen ... is *not really bothered*". The reaction will occur so the chlorine atom will "feel more stable." Tajinder knows that at this stage of his course that this explanation is "not really very good" and so concludes that he does not know the answer.

§A28.2.2: Tajinder discusses electronegativity.

Further evidence of Tajinder's difficulty in finding an alternative idiom to discuss his chemistry occurred in the next interview where he reported that a hydrogen atom "*announces* that it *wants* an electron, or it *wants* part of a share of an electron" (T12.C175), and it makes this 'announcement' "by its presence" (T12.C175). Earlier in the same interview there had been some discussion of why a hydrogen molecule is non-polar, and Tajinder had explained that as the atoms in the molecule had "got an equal amount of electronegativity, they pull the electron an equal amount so there isn't really a ∂+ and ∂- end of the molecule" (T12.A224), an argument that uses the language of electrostatic forces (electronegativity, pull), although it does not link in with the reasons for electronegativity values (*i.e.* core charge, nucleus-electron distances). However at the end of the session when we were recapping, I picked Tajinder up on something he said,

I: Mm, so in diagram number 7 the argument was that both hydrogens pull on the electrons equally, so it's going to be neutral at each end,
T: We want it to be neutral at each end, don't we?
I: Why do we want it to be neutral at each end?
T: Because we want it to be a neutral species.
I: Why do we want it to be a neutral species?
• • • • [pause, c.4s]
T: It's not whether we do, ... it just is.
T12.D003

This line of discussion was of interest as it seemed to be another example of where Tajinder did not distinguish the reasons for a particular phenomenon occurring, with the evidence for the phenomenon: in other words when asked for the reason for something happening he would instead give the reasons why *he knew* it to happen. This suggested that Tajinder did not share the orthodox scientific perspective on cause and effect, that would enable chemical processes to be explained using electrostatic principles. In this context Tajinder explained that,

> "... if we just go on the principle that ... the electronegativity [is] the same, therefore the pull is the same, and if we go on that principle, then we figure out that each hydrogen has 50:50 pull on each electron, and if you add 50:50 you get 1, you get a hundred [percent?], so each electron will have full ownership of 1 [electron]. But then we could go on the principle that we know hydrogen is neutral [*i.e.* non-polar] as a species, then therefore how much pull does each hydrogen have on each electron, which will be 50:50."
> T12.D013

In terms of making logical deductions Tajinder was right, but I was interested in finding out whether Tajinder thought it was ***appropriate*** to claim that the equal pull from the hydrogen nuclei on the electrons was ***because*** of the non-polar nature of the molecule. On this occasion Tajinder did ***at first*** seem to appreciate the distinction when it was made explicit for him, but then he changed his mind,

> I: ...Is the molecule neutral because the two hydrogen nuclei pull on the electrons equally, or do the two hydrogen nuclei pull on the electrons equally because the molecule is neutral?
> • • • • • • [pause, c.6s]
> I: Or both of the above, or neither of the above?
> T: The, both of the - both of the hydrogens don't pull on electrons to become neutral, to - for it to be, for it to be neutral.
> I: What, you're saying that's not the reason they do it?
> T: No. Because then, when, when you bring two things together, you can't tell it don't be this electro¬ (negative) oh, oh, they might, both reasons actually, would it be both reasons?
> T12.D039

From a scientific viewpoint an argument that hydrogen nuclei pull on electrons equally in order to make a molecule non-polar would be seen as teleological. However the argument need not be teleological if atoms were sentient actors in nature. Tajinder uses anthropomorphic language - "you can't tell" the atoms how electronegative they should be - and it seems to be at this point that he changes his mind, and accepts the validity of the [teleological] argument. As the discussion proceeds Tajinder continues to use anthropomorphic language,

> "if talking about the actual species and what is happening when they react, • • • they can't *decide* 'oh we *want* to be neutral so I'll only pull on you a little bit', ... if that happened then they wouldn't have [a single] electronegativity value, would they? ... Because, then, ... say you had the fluorine, yeah, and the fluorine come along to came along to ... a ... metal ion, and it *said* 'I'm only going to pull on your electron a little bit because we want to be a neutral species', ... so therefore ... the value of the fluorine *saying* 'all right, I'm going to pull you in' ... doesn't *say* to the potassium, 'right just because you're a potassium, I'm not going to pull your electrons in further', than if it was a calcium."
> T12.D055

Tajinder's argument here seems to be that as elements are assigned a particular electronegativity value they can not arbitrarily decide how much to pull electrons in particular contexts. However in this extract, Tajinder does not ***appear*** to consider that discussing the issue in terms of atoms having conversations about such matters is itself problematic. Yet as the discussion continues Tajinder attempts to move beyond the anthropomorphic language of the OCTET RULE EXPLANATORY PRINCIPLE, to use the concepts of the COULOMBIC FORCES EXPLANATORY PRINCIPLE,

> "[the fluorine atom] doesn't make a conscious decision to pull in... aluminium electrons more [sic] than the erm potassium, it's just that to do with the size of the ion, the size of the atom that it's going to bond with, and the electronegativity value of that other atom, isn't it? ... It's always got one value, of how much it's going to pull in, but it just depends on the atom, how much it does show on when you draw the electron density."
> T12.D113

Tajinder uses anthropomorphic language to give "a definition of electronegativity", (T12.D149),

> "say we know what the definition of electronegativity is, we say that the fluorine *says* to the potassium, erm, • • 'I *want* an extra electron to become stable, and what *I'll do* to get that electron is take it off you', and it'll just take it off the potassium, or in the bond that it forms, in the ionic bond that it forms, it'll take it completely away from the potassium, therefore *thinking* that it has electron which it has,... because the electron density is all... shaped around the fluorine."
> T12.D149

But actually, he knows there is no 'atomic conversation',

> "[the fluorine] doesn't say anything to the [potassium ion] it ... *indicates* ... by the distance at which it takes it away from the the a¬, the bonding atom."
> T12. D164

Tajinder was aware of how his way of thinking and talking about chemistry had become habitual, and was limiting his progress. At the start of the next session he explained his feelings about this,

> "going through my course, ... if I hadn't have done ...some aspects of chemistry G.C.S.E., I would have found this like easier to understand maybe, because like what, what they taught us at G.C.S.E. and what they teach us now like contradicts itself, as it were, and like it's harder for you to understand, 'cause they ham [sic] it into you that you have to learn this for this exam, and then you learn it and then you remember it, and then when I do this course, or when you teach me, or [the other chemistry lecturer] teaches me, I always think of that thing that I learnt for G.C.S.E. and it sort of like clashes, therefore like it's harder to remember sometimes."
> T13.A019

Tajinder now felt that what he had been taught at G.C.S.E. was "not very close to the truth" and "it can't really be developed because you have to think in a different way" (T13.A044). He gave the example of bonding, where,

> "they tell you like erm, a covalent bond is sharing electrons, ionic bond is er, giving and take, accepting and donating electrons, and that's the end of it. Well I know A level develops that sort of same theme, but it's like quite different. They could of [sic] taught it a it in a bit more depth at G.C.S.E. I think."
> T13.A048

Tajinder felt that in the first year of his course this had confused him quite a bit, but that he had "got round it" now (T13.A056). The evidence from the case study suggests however that the complex of ideas he had built around his OCTET RULE EXPLANATORY PRINCIPLE was still channelling his thinking and language to a considerable degree.

UNDERSTANDING CHEMICAL BONDING.

Appendix 29.

Tajinder's explanatory manifold.

§A29.0: Tajinder's manifold explanatory scheme for chemical bonding.

At the start of his course Tajinder's explanations of chemical bonding were largely derived from what I have labelled his OCTET RULE EXPLANATORY PRINCIPLE (see chapter 8, §8.2.1). As he progressed through the course Tajinder acquired and applied two further explanatory principles, based on Coulombic forces, and on minimising energy. Although these two principles were closer to the CURRICULUM SCIENCE understanding of bonding, and were potentially able to explain aspects of the topic that were outside the range of convenience of his OCTET RULE EXPLANATORY PRINCIPLE, they did not supplant it. Rather, Tajinder continued to present arguments based on the OCTET RULE EXPLANATORY PRINCIPLE, alongside his COULOMBIC FORCES EXPLANATORY PRINCIPLE, and his MINIMUM ENERGY EXPLANATORY PRINCIPLE Tajinder's comments about 'G.C.S.E.' and 'A level' explanations, presented earlier (see appendix 28, §A28.1.1), demonstrated his awareness of the plurality of his thinking. It would appear that he was able to conceptualise his own learning in 'toolbox' terms (see chapter 1, §1.7.2). This plurality may be demonstrated by considering some of the research interviews during his final two terms of A level chemistry.

§A29.1: Tajinder offers three explanations of the bonds in molecular oxygen.

In interview T16 (January 1994) Tajinder explained why oxygen atoms would join together to form a molecule. Spontaneously he gave an answer in terms of his OCTET RULE EXPLANATORY PRINCIPLE,

> "If we have just one oxygen atom it's got erm • six electrons in its outermost shell ... and, erm to become stable it wants an octet •• state, well it wants eight electrons in its outermost shell to become stable, as it were. And then another oxygen with the same arrangement comes along, or is present. And a way for it to erm bond together, for both the atoms to have full outer shells or eight electrons in this outer shell is to share two electrons"
> T16.A224

And,

> "each oxygen atom starts off with six electrons in its outermost shell, and it wants to gain two electrons, by some method, erm, to have a full outer shell, eight electrons in its outer shell to become most stable. And erm a way of doing this is by gaining or by sharing two electrons with another oxygen atom. Erm the other oxygen atom is in the same situation so it can share an electron with the other, with another atom, so it thinks it's got a full outer shell."
> T16.A243

When the use of the term "want" was queried, Tajinder decided it is not a good word to use. However, he did not seem to find "thinks" inappropriate in the context of atoms. Even when "happy" was introduced into the dialogue, he did not find such language problematic,

T16.A254
I: When you say it wants to gain two electrons,
T: Oh, erm, so 'wants' is not really a good word.
I: Why is 'wants' not a good word then?
T: (Wants?) Because it's not consciously thinking that it wants.
I: It's not? ... So what's this about 'it thinks it's got eight' then, afterwards?
T: Thinks it's got eight.
I: ... Does it think it's got eight?
T: Erm, yes I think it does think it's got eight. Otherwise ... it wouldn't happen.
I: So how many does it think it's got to start with?
T: Six.
I: And does it want eight?
T: It wants eight.
I: And when it thinks it's got eight, ... it's happy it doesn't do anything else?
T: Yeah, it's quite happy.
I: Is that a fair way of putting it?
T: Yeah.
I: Quite happy.
T: Yeah.
I Is it quite happy the way you or I might be quite happy?
T: Yeah. All right,
I: I mean seriously?
T: E:rm.
• •
T: No, well,
I: I mean you said that with a smile on you're face ...
T: Erm,
• •
T: not in the, not, well you can't really compare it to us, it's just like it's stable the way it is, but then if something else comes along and reacts with it, it might be more stable, in another way.

So here "happy" seems to be taken by Tajinder to mean *stable*. It was pointed out to Tajinder that he often gave explanations in terms of words such as 'wants' 'needs' and 'like', and he felt this was "not that good" (T16.A272). Tajinder could not really explain what he meant by such words in this context, but offered to provide an alternative explanation of the bond in oxygen in "energy senses" (T16.A272).

> "Well an oxygen starts off as, ... okay can say the electronic configuration is that, $1s^2\ 2s^2\ 2p_x^2\ 2p_y^1$ and $2p_z^1$, and then it's got two gaps that need [sic] to be filled, oh erm {laughs} e:r that can be filled, with electrons ... And erm to become more stable, or at a lower energy, it can gain two electrons, erm to become, to move down in the energy state, therefore becoming stable, more stable, and so, erm, because there's a gap there, there's a tendency for other elec¬ for covalent bonding to occur, as in the case of O_2, erm where electrons can be shared, so therefore, ... the atom can be at a lower state in energy terms, and therefore more stable, and that's why any thing, any thing takes place [part] in bonding, or any species takes place in bondings in order to er lower the energy state or become more stable."
> T16.A272

Tajinder thought this answer would give him more credit in an examination. This response was derived from Tajinder's MINIMUM ENERGY EXPLANATORY PRINCIPLE, which he did not seem to be able to integrate with his COULOMBIC FORCES EXPLANATORY PRINCIPLE, so although he could postulate a lowering of energy level as the driving force for reactions, it provided him no mechanism for explaining how bonds formed. At this point in the interview I asked Tajinder to attempt a third explanation of the oxygen-oxygen bond, but using the ideas of force and charges,

> "So I've drawn erm, two, two atoms, oxygen atoms, and overall their core charge, which is their nuclear charge minus shielding electrons, is er plus six, 'cause the core charge, nuclear charge is plus eight 'cause its got eight protons in it, and there's two shielding electrons, which are minus two so overall is plus six, on each one, erm, and the placement of electrons, so we can forget about the 1s shell 'cause it's gone into the core charge, so we've got 2s orbital, we've got $2p_x$, $2p_y$ ... and $2p_z$. Now in the $2p_x$ orbital we've already got two electrons in there and the maximum an orbital can hold is two electrons, but in the $2p_y$, erm there's only one electron at the moment and the $2p_z$ there's one electron, and erm, the orbitals are a sort of erm a guide roughly to ... where we think electrons exist, ... where they spend most of their time erm due to attractions repulsions between other things, and ... other charges in the erm atom, or in the species, so there's a plus six charge, and there's six electrons in the outershell, but there's ... a gap in the $2p_z$ and the $2p_x$ orbitals, where there's erm an electron short, where where an electron could be filled, and that plus six charge erm can attract electrons from another species to pull into there, or just to gain an attraction for it."
> T16.A346

At several points, as his explanation continues, Tajinder can be heard to interrogate himself, to see if he is still following the set task. These 'asides' are italicised in the following extract,

> "Well 'cause this is the sort of theory that works for van der Waals' forces, *isn't it?yeah it is*, sort of the attraction erm between opposite core charges and electrons in other species, that's how van der Waals works, *but then I just, that's what I just thought of, and then I thought it can't really work for a covalent bond, I suppose it can, yeah okay, I'll carry on.* Well there's sort of erm, there's an empty space to be filled in the $2p_x$ and $2p_y$ orbitals, and erm when another molecule, when another species comes near enough which is another erm, oxygen atom, the same thing is going on over here, so erm, then er, • • • so then, so then the electrons are attracted to one another any they form a bond."
> T16.A377

The attraction was between "the core charge and electrons in the bond" (T16.A403). When asked to consider the three explanations he had constructed Tajinder did not "think any single one is totally correct" but rather that "you can take bits out of each of them to make a best answer" (T16.A416). He thought " the third one would be the best one" if the question was 'what is the bond' (T16.A427).

So in this interview Tajinder had spontaneously offered two alternative explanations of the bonds in oxygen, from essentially different conceptual complexes of ideas (derived from the OCTET RULE EXPLANATORY PRINCIPLE, and the MINIMUM ENERGY EXPLANATORY PRINCIPLE), and had been able to provide a third explanation (from the COULOMBIC FORCES EXPLANATORY PRINCIPLE) when asked to explain the same phenomenon in terms of charges and forces.

§A29.2: Tajinder tends to use an amalgam of two explanatory principles.

At the start of the next interview session (T17) Tajinder could not specifically remember the three distinct 'stories' he had used to discuss bonding, although he expected it to, "come back" to him, as we talked (T17.A012).

The first to 'come back' was the OCTET RULE EXPLANATORY PRINCIPLE, which Tajinder applied when considering the sodium atom, which,

> "would lose an electron, from its outermost shell to form an ionic bond ... because of the structure of the atom. It's got one electron in its outermost shell and it *wants*, to become stable it *wants an octet*, erm, i.e. erm, a *full outer shell* with 8 electrons, similar to noble gases, and the easiest way of doing that is by removing an electron from its outermost shell, • to become an ion, it's most stable, more stable."
> T17.A051

Shortly after this the MINIMUM ENERGY EXPLANATORY PRINCIPLE was brought into use, *alongside* the OCTET RULE EXPLANATORY PRINCIPLE, to explain why a covalent bond would form between two hydrogen atoms,

> "to either, erm, lose an electron or erm gain an electron it takes a lot of energy to do that, so it doesn't *want* to go through that process. So the easiest way of becoming more stable or having a full octet is by sharing electron with another hydrogen.... [They do not stay as separate atoms as] they *wanna* become more stable, so they erm *wanna* full octet, in this case, because it's in the 1s it *wants* erm 2 electrons"
> T17.A081

Soon after this Tajinder remembered that "everything forms bonds in order to become more stable, or at a lower energy" had been one of the three perspectives he has used in the previous interview (T17.A132). One had been "full octets", and one had been "energy" which was "the same as stability", but he could not bring the third mode of explanation to mind (T17.A150). A context was introduced where the OCTET RULE EXPLANATORY PRINCIPLE could not provide an explanation, to see if Tajinder would appreciate the shortcoming. He was asked to explain why the bonds in tetrachloromethane were polar in 'octet' terms. Tajinder began to use some electrostatic notions,

> "each species on the periodic table has erm, electronegativity value, and erm that that value determines, ... how much a species can either pull in ... electrons, to pull in ... electron density towards itself. And the most electronegative species is fluorine, and chlorine is quite electronegative as well. And, • • • • so it pulls in the electron density from the carbon towards itself, and as it has more electron density around itself it's slightly ∂-, I think."
> T17.A177

Tajinder agreed this was ***not*** an explanation in terms of octets, and had a second attempt at constructing such an explanation,

> "in the chlorine atom there is [sic] seven electrons in its outermost shell, so there's like, erm, a a gap where another electron should be placed to have perfect erm spherical density around the erm - nucleus, so where, as there's an electron missing there's sort of a gap that appears, and that gap is erm, erm, where an electron should be, so due to the electronegativity of erm chlorine if another electron from another species appears, somewhere nearby, and can fill that gap, then the chlorine would pull it in to have spherical erm, density, or so it ***thinks***, so it ***thinks*** it's got spherical density."
> T17.A202

Here the references to the "gap" in the electron density, where the "missing" electron "should be", and the atom "think"ing it had spherical electron density are mixed with talk of the electronegativity of chlorine, and the "pull" it can exert on an electron. In terms of 'stability' (the MINIMUM ENERGY EXPLANATORY PRINCIPLE),

> "it forms because when each individual erm atom is by itself it's at a certain energy level, and erm you can see [sic] the chlorine is not stable as it is, neither is the carbon, not fully stable. So erm in order to become more stable erm it forms a bond with something, in order to erm decrease the energy that it's at, so it becomes more stable, and that's why that's why species form bonds."
> T17.A242

Tajinder does not explain ***how*** one can "see" that chlorine and carbon are not stable, but when he was pushed to explain why the product was at a lower energy, he resorted (after a pause for thought of about 19 seconds) to his OCTET RULE EXPLANATORY PRINCIPLE,

> "it's at a lower energy level because when each individual species is, is by itself, as I said like chlorine has 7 electrons in its outer shell, and the only way it can become more stable than it is is to have a ... full octet, and that is to gain an electron to become a chloride ion. • • • (Why is it more stable?) • • • • Oh because of the erm electron density being erm totally spherical because it's got the right number of electrons, and, mm, • • • • • • • • yeah."
> T17.A252

Shortly after this Tajinder was asked whether two adjacent hydrogen atoms would remain separate, and he then realised "the third reason [for explaining bonding was] due to attractions and repulsions" (T17.A277). He gave the following explanation,

> "on the atoms there is the nucleus which is positively charged and there are electrons which are negatively charged, and erm,...opposite electrostatic forces [sic] attract, and there's an attraction between one nucleus and adjacent erm electrons on another molecule, on another atom, so that interaction also forces the er atoms together, and that forms a bond, well ... that helps in forming a bond. In some cases that is a bond like in er van der Waals forces that's a force but it's a type of bond. [The hydrogen atoms] come together, well the positive ... nuclei erm attract adjacent erm electrons, and they come together and they form a sort of equilibrium because they can't keep on going together because of repulsion between the ... two electrons and between the two ... nuclei."
> T17.A277

This explanation was constructed from the COULOMBIC FORCES EXPLANATORY PRINCIPLE, although there is still a suggestion that for Tajinder - even when cued into this complex - a bond needs to be something *more* than *just* forces. So as in the previous interview, Tajinder had demonstrated that he could apply ideas from three separate complexes, and as before the COULOMBIC FORCES EXPLANATORY PRINCIPLE seemed to be the one that came to mind less readily.

As has been already mentioned, Tajinder did not seem to form a substantial links between his COULOMBIC FORCES EXPLANATORY PRINCIPLE, and his MINIMUM ENERGY COMPLEX. Although the minimum energy complex provided a rationale for why chemical process occurred, it did not incorporate the means for explaining mechanisms (such as is provided by the concepts of charge and force). Having just explained the bonding in the hydrogen molecule in electrostatic terms, Tajinder was asked to give an explanation "in terms of stability and energy levels". As Tajinder did not link energy ideas with force and charge his response incorporated features of his OCTET RULE EXPLANATORY PRINCIPLE,

> "the most stable atoms in the periodic table are the erm, noble gases, because they have a full outer shell or full octet, so erm, because having a full octet they don't *want* to precipitate [sic, participate] in bonding, they don't *want* to either lose [electrons] or bond, they're *happy* as they are. So erm • • when you have two hydrogen atoms ... separately, erm they have one electron ... each and to have a full octet erm they either have they either have to lose an electron, or no they have to gain one electron each, and the easiest way of doing that is by forming a covalent bond, which they form and once they do that they're at a lower energy than they were previously. That's why they do it."
> T17.A308

As the interview continued, Tajinder was probed to see if he would integrate aspects of his COULOMBIC FORCES EXPLANATORY PRINCIPLE with his other ideas.

Tajinder applied his MINIMUM ENERGY EXPLANATORY PRINCIPLE to the noble gas elements, which "don't really react with anything, they're like *happy* as they are ... because they're at the lowest possible energy - level that they can be at" (T17.A325). This was explained in terms of electron density, but from using the language of the OCTET RULE EXPLANATORY PRINCIPLE,

> "like a neon atom it's got eight electrons in its outermost shell, and it's got ... a spherical electron density around it, and erm if it *wants* to take place [sic, part] in bonding ... i.e. either I mean erm ionic, polar or covalent bonding, not like van der Waals' or anything... it either has to gain an electron, or lose an electron or share electrons, as it were ... And, erm, they have a total electron density around it, and if they *wanna* form a bond, they have to break the electron density either add to it or take some away, and there's energy required to do that, and it's not erm beneficial to, so you could say, for it to do that, and it's like at it's lower en¬, so it's erm stable as it is."
> T17.A325

Again Tajinder seems to distinguish real bonding ("ionic, polar or covalent bonding ...") from just forces ("...not like van der Waals"), a common feature of learners' explanations in this study which is illustrated further in chapter 11 (§11.7).

Although by this final stage of his course Tajinder freely uses the abstract concept of electron density, in explanations such as that above spherical electron density takes on a heuristic role in substitution for full electron shells, and the argument remains at either an anthropomorphic, or teleological, tautological level,

> "I would think that it's quite stable because it's formed a covalent bond, or ... what looks like to be a covalent bond, and erm, seems quite stable, otherwise otherwise it wouldn't have formed a covalent bond in the first place"
> T17.B056

Later in the same interview Tajinder discussed metallic bonding using a mixture of ideas derived from the MINIMUM ENERGY and OCTET RULE EXPLANATORY PRINCIPLES,

> "Metallic bond is ... is where, you have, erm a metal and you have positively charged ions, and you have erm delocalised electrons which is [sic] like a sea of electrons around the ions. Which makes, which forms the metal which is quite stable, well it's stable relative to what the at¬ element is. ...[because] it's got a certain amount of erm electrons in its outermost shell and erm instead of like in the case of sodium where it - gives away the electron, erm, the same thing occurs here, well it's not really given away it's sort of delocalised, so the electron is allowed to move around in er certain orbitals, around each of the Fe erm ions, so that's, so it becomes stable, because it forms an ion, and, but there's still electrons around it ... [so] when it comes down to it the Fe's formed an octet, so it's more stable."
> T17.A548

This mixture of ideas derived from both the OCTET RULE EXPLANATORY PRINCIPLE and the MINIMUM ENERGY EXPLANATORY PRINCIPLE is also apparent later in the interview when Tajinder explains that sodium metal and chlorine gas,

> "reacts to become • • even more stable, • than it already is. Because ... in the chlorine there is a covalent bond between the two ... atoms to form a molecule, but, actually ... the chlorine nucleus ***thinks*** that it has a full outer shell. • • Er:m, • • wait no, that's not really a good way of explaining it. Okay erm, • • • • • • ... Well when they form, they form to become more stable, ... they ***want*** to have a full octet, or they ***want*** to have erm spherical electron density. But in the case of chlorine, ... if you was to draw the electron density - out, ... it wouldn't be totally spherical around each ... nuclei. And - to have total stability, or to be as stable as you can be, is to have a total electron density - spherical around your around the nucleus. And, • • erm so in chloride - ion it goes some way to do that to become erm, it's more stable, because when you have a chlorine atom by itself it's got quite a gap in it, we can say it's got quite a gap in it. In the ... molecule it's got less of a gap but it's still not fully erm covered you can say, and the same as erm, in the in erm the sodium, that the sodium ***wants*** to totally disown the electron to have a full octet - around it, but in in sodium metal erm the electron is delocalised, to, but ... there's still some erm, electron erm, interference, with it. ... And erm when they form together, the chlorine ... atom and the sodium atom, they form together, and the sodium ... gets rid of its outer electron to a chloride, so it's got total electron density around itself. And it's got also a full octet, and the same as in the chlorine, it's got total electron density around itself, and when it has total electron density, it, it is at its most stable, I think."
> T17.B180

Again there is no mechanistic aspect to this explanation, and when Tajinder was asked if the chlorine atom was aware of its electron density, he replied that "yes it is aware, because if it wasn't then it wouldn't try and form bonds with other things, it wouldn't react with other things" (T17.B230). At this point in the interview Tajinder was referred again to the the hydrogen molecule, the context in which he had previously used the COULOMBIC FORCES EXPLANATORY PRINCIPLE. At first Tajinder suggested that although the electron density around a hydrogen atom was spherical (T17.B265), in this case two hydrogen atoms would come together because the molecule "will have more spherical electron density" (T17.B280). However Tajinder realised that this scheme did not work, and that the hydrogen molecule did not fall apart, even though this ***would*** provide the atoms with more spherical electron density (T17.B280). Rather the two atoms came together "because of electrostatic forces" (T17.B293). After some leading questions Tajinder suggested that perhaps the reaction between sodium metal and chlorine gas could be due to "electrostatic forces again" and he wondered if we could "put that view into it?" (T17.B328). However, when Tajinder had another attempt to explain the reaction he reverts to his MINIMUM ENERGY EXPLANATORY PRINCIPLE. He thought that, in general terms,

> "we can say that bond breaking uses up energy, and bond-making or bond-forming gives out energy, and in order for something to react, ... for a reaction to take place or be feasible the ΔG value of the reaction has to be negative,... everything will come out to be negative when you work out $\Delta H - T\Delta S$, when you look at that, when you look at all the contributing factors, the overall value will be negative therefore the reaction will be feasible."
> T17.B401

Tajinder explained that in this particular example,

> "in order for a sodium... to exist as an atom, to move away from the, from the metallic, from the other species in there, erm a certain amount of energy is needed to remove that one, and also a certain amount of energy is needed to break apart that covalent bond, but this happens because the overall, the energy given out when the sodium bonds with the chlorine is far greater than the energy first needed to break the two bonds, • • so therefore your reaction takes place."
> T17.B419

In its own terms this was a perfectly valid answer, but Tajinder was unable to give an explanation of *how* this happened at the molecular level.

Tajinder was given a further opportunity to explain a reaction to see which principle(s) he would apply. He was asked why hydrogen and chlorine react to form hydrogen chloride, and he realised that "we can't really say, on, ... the full octet level, because all three have got full octets" (T17.B506). Instead,

> "the only way we can discuss it, is, ... energy levels, that when we have hydrogen gas and we have chlorine gas they're at a certain energy level, but then when these two mix, or when they react and they form a new product the hydrogen chloride is at a lower energy, than the hydrogens and the chlorines."
> T17.B506

Some thought went into a consideration of why the product might be at a lower energy, before Tajinder suggested this was,

> "because the chlorine is ... electronegative, and the hydrogen is electropositive, e:rm in, in [the reactant molecules, hydrogen and chlorine], each species, each nuclei, has got equal electron density distribution - around itself, but in the [the product molecule, hydrogen chloride], the chlorine has got more electron density towards itself, and that's what it *wants* to become more stable, and the hydrogen also *wants* that, it *wants* to either ... gain an electron to become stable, or ... lose an electron, but lose an electron is not very likely."
> T17.B517

Tajinder felt that "the only way" he could "explain it is to do with the ... electronegativity values, and the electron density", but he could not "*really* explain it, [as] it's quite a hard, hard question" (T17.B517). He thought that the hydrogen molecule "*knows* that it's stable" before the reaction (T17.B534), and the atoms in the chlorine molecule were aware they would rather completely gain an electron, than share with one another: that is, "*they are aware* otherwise it wouldn't happen" (T17.B541).

So although Tajinder could construct explanations based on his COULOMBIC FORCES EXPLANATORY PRINCIPLE, and did so so in some contexts, he did not always bring these ideas to mind when it might be judged from a CURRICULUM SCIENCE perspective to be appropriate. He was more likely to use a mixture of ideas about minimising energy, and obtaining full shells, or - a more sophisticated version of full shells - spherical electron density.

§A29.3: Tajinder uses different explanatory principles to explain different reaction mechanisms.

The pattern established in interview T16 and interview T17 continued in the next interview (T18) when the free radical reaction between chlorine and methane was considered.

Tajinder's explanations largely used a mixture of ideas from his MINIMUM ENERGY EXPLANATORY PRINCIPLE, and his OCTET RULE EXPLANATORY PRINCIPLE. He explained that here, as in other reactions, "reactants start off at a higher energy, and erm, in order to form and to form a product, the products have to be at a lower energy, i.e. be more stable, otherwise there's no point the reaction occurring" (T18.A283). In the first propagation step Tajinder thought "the free radical of the chlorine is attacking a methane molecule" (T18.A333), although he was "not too sure why ... it's attacking the methane molecule" (T18.A346). Later he suggested that,

> "the chlorine attacked, because er chlorine is at higher energy, high energy and it *wants* to become more stable, so it reacts with something ... to become more stable, and in this case it was a hydrogen."
> T18.A430

Tajinder explained another propagation step, a methyl radical reacting with a hydrogen molecule, in the terms that

> "the free radical has a ***desire*** for electrons, it's just a ***desire*** for electrons, and erm, when this comes close to a chlorine it ... it it ***tries*** to take, it ***tries*** to bring electron density ... because it wants to pull in electron density because it's electron • poor, ... so it brings, it *wants* to bring electrons, to form a bond with, and the only way of doing that is by splitting up this chlorine, and the only way that chlorine can split up to form another free radical is by undergoing homolytic, homolytic fission, so it forms two free radicals, and one of the radicals attacks the methyl group."
> T18.A477

Tajinder thought that the chlorine molecule knows that the methyl radical has this desire for electrons, "otherwise it wouldn't happen" (T18.A493). The carbon atom in the methyl radical has

> "got 7 electrons in its outermost, in its valent shell and it *wants* to become stable, it *wants* a full octet, so in order to do that it ... it has to get some electron density, electrons from somewhere, electron density, to form a bond with, so it's got desire to do that."
> T18.A500

So Tajinder thought that the carbon atom "want"ed an octet. It would seem that it could only achieve this if the chlorine atoms in the molecule ceased to have an octet. However Tajinder thought this was acceptable in this case,

> "Because when you have a chlorine molecule, they're of erm equal electronegativity, so that the bond, the electron pairs are shared equally between them, but when you have a carbon-chlorine bond the ... chlorine ... is more electronegative than the carbon, so it has greater *desire*, it has more tendency to pull electrons towards itself, therefore it has more, you can say, more electron density around it, so it has more share of electrons. So it's more stable that way"
> T18.A513

The methyl radical influences the chlorine molecule "just by its presence" - "they would bump into each other, and ... if the ... carbon free radical bumps into the chlorine, ... then it just happens" (T18.A539) "because the products would be at a lower energy [than] when they were in the reactants" (T18.A547).

Tajinder continued to explain the rest of the steps in the reaction mechanism in the same terms. He was asked to consider again the reasons *why* the steps occurred. Tajinder admitted that he "didn't really know the answer", and that when he did "think of something there's always some like catch to it" (T18.B209). He attempted to explain the reaction from the perspective of electronegativity,

> "the hydrogen is electropositive, and ... in the carbon-hydrogen bond because the carbon and the hydrogens are similar erm erm electronegativities it's not really a polar bond present there, and so the electron density is slightly, slightly more towards the carbon, but it's sort of like in the middle, but when, but when there's a erm hydrogen - chlorine because the chlorine is erm more electronegative it has more pull on electrons towards it, and that *pleases*, well that, hydrogen *doesn't really mind* and it's more stable in that state so, when it forms a carbon-chlorine bond it's more stable than a carbon, • hydrogen-carbon bond."
> T18. B209

So once again the explanation was largely anthropomorphic. The difference in electronegativity was "to do with erm the electron density and the number of protons and everything, the size of the atom and everything", so chlorine was "more electronegative, has a greater *desire* for electrons" (T18.B232).

Throughout his discussion of this reaction Tajinder failed to significantly use his COULOMBIC FORCES EXPLANATORY PRINCIPLE, even when applying conceptual 'tools' such as the electronegativity and electron density concepts that might be expected to cue him into this way of thinking. However when Tajinder had exhausted his consideration of the chlorination of methane, a new context was introduced - the bromination of ethene. Although another example of halogenation of a hydrocarbon, this was a different type of reaction (electrophilic addition with an ionic mechanism, rather than free radical substitution), and in this context Tajinder did start to think in terms of his COULOMBIC FORCES EXPLANATORY PRINCIPLE. The bromine molecule had "induced polarity" with one end being "electron deficient, so it's ∂+, so the electrons have moved slightly towards the ... the other bromine" (T18.B295), and,

> "the pi bond is broken by an electrophile, which forms ... a transition state, and erm, because it's got a plus charge on it and the bromine is er ∂- they attract one another and they form a bond, so that, erm, so therefore 1,2-dibromoethane forms."
> T18.B276

Tajinder's scheme actually had the wrong poles of the bromine molecule 'attacking' the wrong part of the ethene molecule, but he did have "the ∂+ and ∂- ... join onto one another to form a bond", (T18.B295), as "there's a ∂-, and the ∂+ and they come together and they form a bond because opposites attract" (T18.B317). Tajinder recognised that "that's another explanation of why it occurs" (T18.B317). In the next stage of the reaction,

> "we've got a negative ion, and we've got a positive ion, so they're attracted to each other, and erm they form a bond, where there's electron movement from the negative, erm, in¬ intermediate between the bromide ion and the carbon positive ion, to show the formation of the bond as well."
> T18.B453

In interview T18, then, Tajinder spent some time (over an hour) discussing in detail two chemical reactions involving the halogenation of hydrocarbons. In the second example (an electrophilic addition) he was able to explain the mechanism in electrostatic terms: attractions between opposite charges causing movements of electrons, thus causing bonds to break and new one to form. However in the context of a free-radical mechanism Tajinder instead applied a mixture of arguments about the tendency of systems to move to lower energy states, and references to what atoms *wanted* and *desired* in terms of octets or electron density.

§A29.4: Tajinder applies two different approaches to explaining the two different types of bond in ice.

Tajinder continued to call upon all three complexes for explaining bonding as he completed his course and revised for the final examination.

For example in interview T19 Tajinder explained that in ice there are hydrogen bonds between the molecules, as well as polar bonds within the molecules. He explained that the polar bond held the atoms together "because hydrogen and oxygen both contribute to that bond, so they've got part share of it" (T19.A323). This holds the atoms together "because in the [water molecule] atoms make up a full octet, or they *think* they do, to become more stable",

> "because each have a ... share of the electron density, or each have a share of the electrons, in the bond, and they do that to become more stable, which they are because hydrogen can either lose one or gain ... one electron to have a full octet [sic], two electrons in the outermost shell, and oxygen... already has six and to gain another two it ***thinks*** it's got a full octet which is ... noble gas configuration."
> T19.A329

As well as explaining the bond in terms of his OCTET RULE EXPLANATORY PRINCIPLE, Tajinder was able to discuss the bond as orbital overlap,

> "oxygen has got electronic configuration of 2.6, and ... it's got one full p-orbital, and it's got two half-filled p-orbitals, and they're able to overlap with other orbitals to form bonds, ... and on the hydrogen there's just an ... s-orbital, 1s orbital with one electron in it, and that's able to overlap with the p-orbital, from the oxygen to form a bond. So the bond is just [the] overlap of orbitals."
> T19.A 360

Although Tajinder was able to discuss the bond in these terms, he was not able to explain *why* overlap of orbitals held the atoms together (T19.381).

When considering the other type of bond present, however, Tajinder introduced electrostatic considerations,

> "a hydrogen bond is an attraction between a ∂- oxygen and a ∂+ hydrogen in this case, and it's an attraction between the ... two parts of the molecule, ... and it's an attraction, so it's better to think of it as an attraction"
> T19.A381

The part of the oxygen that was '∂-' was the lone pair (T19.A393), and the hydrogen was ∂+ at the "opposite end [to] where the... covalent polar bond is" (T19.A404).

Here then, even within the context of the same substance, water, one type of bond is not discussed in electrostatic terms, but another type of bond is. The hydrogen bond can not be rationalised in terms of Tajinder's OCTET RULE EXPLANATORY PRINCIPLE, and here his COULOMBIC FORCES EXPLANATORY PRINCIPLE is applied. However, the hydrogen bond's failure to meet octet rule criteria for a bond, leads to Tajinder suggesting that rather than considering it as a bond, "it's better to think of it as an attraction". (This suggestion had parallels in the comments of other learners, as is discussed in chapter 11, §11.7.5.)

§A29.5: Tajinder operates with a plurality of explanatory principles for chemical bonding to the end of his course.

In the subsequent interview (T20), Tajinder demonstrated that he *was* able to base his explanations of bonding in electrostatic terms.

So for example, in the case of water discussed in the previous interview an oxygen atom in water could have four bonds (not sensible from the OCTET RULE EXPLANATORY PRINCIPLE, and not necessary if the hydrogen bond is discounted as in interview T19, as above),

> "because erm the two lone pairs of electrons on the oxygen can attract protons from other erm molecules which can form bonds, so there's two hydrogen bonds there, and the two protons, on on that single water molecule can hydrogen bond as well, and so it's four."
> T20.A033

Another example of a bond construed in terms of the COULOMBIC FORCES EXPLANATORY PRINCIPLE was in a hydrogen molecule, where Tajinder reported that,

> "there's attractions and repulsions. There's attraction between the nuclei • of one hydrogen atom for its own electron and also the electron from the other hydrogen, and also the other hydrogen atom nuclei ... attract the electrons. There's a repulsion between the two hydrogen nuclei, and there's a repulsion between the two electrons."
> T20.A557

Tajinder also described the "attraction between the ions" in sodium chloride, but explained that they would not coalesce "because there's repulsions as well" (T20.B040),

> "Because, erm • • this is ov¬ overall one plus, but it still has negative charges on it, and then as it comes to a certain stage there will be repulsions between the two nuclei, of the species and also the electrons, surrounding electrons, so that there's equilibrium where it reaches, repulsions equal er attractions."
> T20.B040

Tajinder described how in the lattice "there's a sodium ion, and it's er surrounded by six chloride ions" in "an equilibrium" (T20.B055); and how the lattice was held together by "attractions between positive and negative ions" (T20.B149).

However, even after demonstrating he could use his COULOMBIC FORCES EXPLANATORY PRINCIPLE in this range of contexts, Tajinder would sometimes select other principles when explaining bonding. In interview T21 Tajinder seemed to use his alternative CONSERVATION OF FORCE EXPLANATORY PRINCIPLE rather than the Coulombic principles he had learnt. He refers to an electron "being held in by the nucleus, because the nucleus is positive and the electron is negative" (T21.458), but states that,

> "the nucleus has *a certain amount of attraction* to electrons, and when there's a pair of electrons it's got a, it's, it's erm, attracted both electrons, and if the distance hasn't change, that means that ... it's attracting both equally, but if one is removed then the other one would be attracted more."
> T21.B464

Another example of Tajinder not selecting to use his COULOMBIC FORCES EXPLANATORY PRINCIPLE occurred in the penultimate interview, T22, when Tajinder explained the dative bond in terms of his OCTET RULE EXPLANATORY PRINCIPLE,

> "I think it's called an adduct, where erm a dative covalent bond takes place, erm this is because erm, Al‐ $AlCl_3$ exists as a molecule, and so does erm ammonia and erm, aluminium like we was talking about before wants has *wants* erm a full octet, which is in this case [sic] is eight electrons, and the ammonia has got er a lone pair of electrons and it also *wants*, well actually it's got a full octet, but erm, it's more stable if it's in this form, er so it form a molecule."
> T22.A366

Later in the interview Tajinder discussed the dative bond in the dimer of aluminium chloride, which was "the same sort of thing" and formed "in order to form a full octet for each of the species involved" (T22.A471), a clear example of the application of his octet rule explanatory principle.

To summarise then, Tajinder commenced A level chemistry relying heavily on his OCTET RULE EXPLANATORY PRINCIPLE to explain chemical bonding and related phenomena. During the course he acquired, and learnt to construct explanations based upon, the alternative principles of the effect of electrostatic forces, and the tendency of systems to evolve to lower energy states. However he continued to base some of his explanations in terms of the octet rule, and as he failed to see electrostatic forces as the ***mechanism*** by which his MINIMUM ENERGY EXPLANATORY PRINCIPLE might operate, he instead described this in teleological terms. Indeed his complex of ideas based around the MINIMUM ENERGY EXPLANATORY PRINCIPLE used the notion of stable patterns of electron density, as a more sophisticated version of full electron shells, and continued to apply the anthropomorphic language associated with the OCTET RULE EXPLANATORY PRINCIPLE.

Appendix 30.

Evidence of learners' difficulties in understanding electron orbitals.

§A30.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 9 develops one of the main themes introduced in chapter 6, i.e. the difficulties students found making sense of ideas related to quantum-mechanics.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 9.

§A30.1: Learners' understanding of the quantum hypothesis.

§A30.1.1: Edward.

One of the colearners, Edward, understood the consequence of the quantum hypothesis on the transitions between energy levels, as "you could put energy into it, ... and the correct frequency, ... which a particular electron would absorb, it would absorb a photon of energy and be promoted to another vacant orbital" (E2.A203). He also knew "the equation energy equals Planck's constant times the frequency of the radiation" (E2.A252). Despite this apparent understanding of how the quantum hypothesis explained the selective absorption of light, Edward did *not* appreciate how the quantization of atomic energies prevented the collapse of atoms. He knew that in an atom there would be forces "between the ... negatively charged electrons and the positively charged ... proton"s (E2.A289), however Edward was not very clear about why this did *not* result in the particles moving closer together.

He compared the atomic context with the solar system, suggesting that,

> "it's something to do with, like the planetary motion, they had some initial kinetic energy, that's why they don't - well attract each other. I don't know, perhaps in creation • • • they was given some initial kinetic energy, and • • • some rotational energy, and that's why they rotate"
> E2.289

Although at the time of this interview Edward was one month from his A level physics examination he did not appear to be aware that classically an atom would be expected to radiate energy as an electrical oscillator. Edward also appeared to be using the term 'attract' to mean something different to the CURRICULUM SCIENCE sense of there being an attractive force between the bodies, rather perhaps to mean for the bodies to move together under the action of such a force. In drawing the analogy with planetary motion Edward was concerned with the problem of where the initial orbital energy came from, rather than why it was not radiated. In the astronomical case the attractive force is gravitational, and the most significant dissipating effect would probably be tidal forces, which would act at a rate *many* orders of magnitude slower than the classically expected effect in the atomic case. The comparison of the atom with the solar system is also considered in chapter 10, where it will be seen that learners' ideas about celestial mechanics may make it a questionable teaching analogy.

§A30.1.2: Kabul.

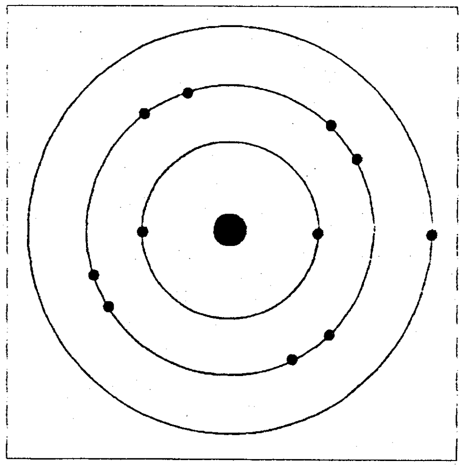
When Kabul attempts to explain thermionic emission in metals he seems to confuse the emission of *electrons* with the emission of *light photons* during electronic transitions,

> "when we heat the metal, the electrons will rise from a lower energy level to a higher energy level, as it's vacuum, {clears throat} the electrons will just jump off there, I mean the metal, if you heat it quite sufficiently, the electrons will will will rise from a lower energy to a higher level and, just be emitted outside ... [for} example if you take iron, if you heat it you will see it turns red, it turns red because it starts emitting electrons, but once it cools down the electrons go back to the electron shells and it regains its shiny colour. • While you're heating the electrons are being emitted, so it gives off colours of different wavelength when you cool down the electrons go back to their original energy levels."
> KT1.A246

§A30.2: Learners' confusion over the relationship between orbitals, sub-shells, shells and energy levels.

§A30.2.1: Edward.

In Edward's first interview (at the end of one year of A level study) he seemed to confuse shells with orbitals, when he described focal figure 1 (which only showed shells) as a "representation of an atom, with er, its electron *orbitals*, erm in different shells, around the nucleus" (E1.2).



focal figure 1

He went on to explain that,

> "there's three electron *orbitals*. Erm, in the first one there's two electrons, in the second, there's eight, and in the third one there's one electron."
> E1.4

When Edward was asked about focal figure 1 in his second interview (near the end of his course) he appeared to use the terms 'orbit', 'orbital' and 'shell' as synonyms. He thought that the diagram,

> "looks like a two dimensional representation of an atom. Erm, with a nucleus in the centre and er these circles representing the *orbits* of electrons.... There's three *orbitals*. In the first there's two electrons, which means that's first *shell*'s full. In the second one there's a full *shell* of eight. And in the third *shell* er there's one electron."
> E2.A024

Edward was asked to explain what he thought the words 'orbit', 'orbital' and 'shell' meant. He explained that "an orbit's just a circular er thing, ... a kind of neat way of describing an electron's motion" (E2.A050). Beyond this, Edward explained that the orbit was not analogous to that of a planet,

> "it looks like a planetary orbit, but in actual fact it's not as simple as that, ... it doesn't ... orbit the nucleus like some kind of planet around the sun."
> E2.A050

Rather Edward thought that the 'orbital' was "a better way of describing it, [i.e.] to say it occupies a volume - of space ... and there's a probability that it will be found in that volume of space" (E2.A050).

§A30.2.2: Tajinder.

When Tajinder attempted to explain the concept of an orbital in his first interview, it seemed he was confused,

> "first lesson here, we was taught, we never learnt this in G.C.S.E., but er, we learnt about, er 1sp, 2sp, $2p_x^1$, $2p_y^2$, was it 2? I'm not sure, I can't remember, but like er this is not like a set that, these [electrons] don't go in pairs, this is like erm an orbital, which I like described before, er *sphere sort of shape*, and like they're opposite, like if this like, I dunno it's hard to describe, if this is a sphere, and has a nucleus in the middle, but one electron would be here, and one on the opposite, and one would be on the opposite side of the orbital. Not, yeah, as in [focal figure 1], but this is like this is - different, because you know there's - er x, y and z axes. Like if you put it on the axes then - it would become clear. So it's hard, it's hard for me."
> T1.B269

In his second interview, Tajinder continued to demonstrate some confusion over the orbital concept, and its relationship to the concept of electron shells, suggesting that "an orbital is just an area around ... the nucleus of an atom, where electrons are likely to appear, or be held", but that there would be three orbitals in a sodium atom (T2.A085), before changing his mind,

> "no wouldn't have three orbitals, it'd have more than three orbitals, erm like you have the s orbital, p orbital, d and the f. Is it the f? I'm not sure. There's four different types of orbitals. And on the p orbitals there's erm p_x^1 p_x, p_y^1 and p_z^1. So I was wrong when I said there was [sic] three orbitals ... I think there's more .... I don't know"
> T2.A085

On reflection, Tajinder was aware that he was confusing material presented to him at A level, with his existing knowledge,

> "what we learnt in G.C.S.E. was erm, which I shouldn't have said, where there's like erm, they draw the sodium nucleus, and they have three rings about it, and that's where they like place the electrons for G.C.S.E. standard."
> T2.A112

Tajinder thought that the rings were "shells" and his G.C.S.E. level model "isn't wrong, but it's not totally correct". However he did not see how the new ideas fitted with the old, at first suggesting, no connection,

> I: Are the orbitals and the shells related in any way, or are they totally separate ideas?
> T: Well, I don't think they're related.
> T2.A123

§A30.2.3: Tajinder.

In Tajinder's fifth interview he discussed how an electron could be promoted to an excited state, but he was not sure whether he should refer to the electron moving between shells, or between orbitals,

> "when you put it into a Bunsen burner, a Bunsen burner's like a lot of heat, and that heat is like energy to the outermost electrons, and when we was drawing the lines, like going up in stages, across the board, erm we was just showing how when you give erm the outermost electron of sodium energy, it rises up to a certain amount, ... then it gains energy, and when it falls back down erm, the energy it gives out is in the form of light, and that is the light it gives out so that's why that sodium has the colour when it gives it out, when, when it's like heated. So it's just the movement of the outermost electron, out of the shells, out of shells? Shells or orbitals, I'm not sure, but it might be like shells, up to an infinite, it could go up to infinite but then there's only a certain amount of energy that's given in, and when that energy is released back it's given out in the form of light
>
> T5.A472

Tajinder was asked for clarification about the 'lines' he had remembered drawing, but he was only able to remember what they were meant to be once he had drawn out his recollection,

> I: Right, what are these lines you're talking about?
> T: {laughs} Erm - shells I think.
> I: Are they?
> T: Or orbitals
> I: Are they?
> T: Erm.
> I: If I find you a piece of paper will you draw them for me?
> T: Okay, I don't mind.
> ... [Tajinder draws a diagram]
> I: I think we need to know what you've drawn. Any idea what you've drawn?
> T: Energy levels.
> T5.A488

§A30.2.4: Tajinder.

In his third interview Tajinder also seems to confuse the orbital with the common diagrammatic representations in terms of a probability envelope. Tajinder seems to suggest that the electron is sometimes outside the orbital, which is,

> "just like erm a probability of finding the electron in that certain area. So that's where like the electrons will mainly be found, like ninety five don't know what the percentage was, but quite high, so then the percentage of *finding that electron in the p-orbital* is also like ni¬ whatever it was, very high."
>
> T3.A460

Tajinder demonstrated a similar confusion in his fifth interview. He thought that there was "just one" orbital in a hydrogen atom (T5.A433), and he was not sure if unoccupied orbitals really existed,

> I: Is it possible to have a hydrogen atom with a 2s orbital?
> T: No.
> I: No. So if you have a hydrogen atom, there's only one orbital that exists?
> T: Erm, well there's one, there's only one orbital that is occupied at the moment.
> I: Ah. Are there any orbitals that aren't occupied?
> T: Erm. Are they any orbitals that are not occupied? Erm. Well an orbital is like, erm, an orbital is just like an imaginary erm sort of area, where you find electron in, so then you could imagine that there would be more orbitals around the hydrogen atom. I'm not sure if they exist or not.
>
> T5.A435

Tajinder suggested a tentative resolution to this question in the following terms,

> "if you find a hydrogen atom and you take a picture of it at that time, then ... [the electron] could be in another orbital, 'cause an orbital just distinguishes a sort of barrier around where you're most likely to find that electron, so it doesn't mean that it just sticks in that one place"
> T5.A450.

Although it was pointed out to Tajinder that the electron would not have left the orbital, even though it might be outside the conventional representation, in a later interview Tajinder still referred to how a 2p electron "doesn't come out that much, like of the p-orbital, well it does come out, but ... it's quite fixed" (T6.B090).

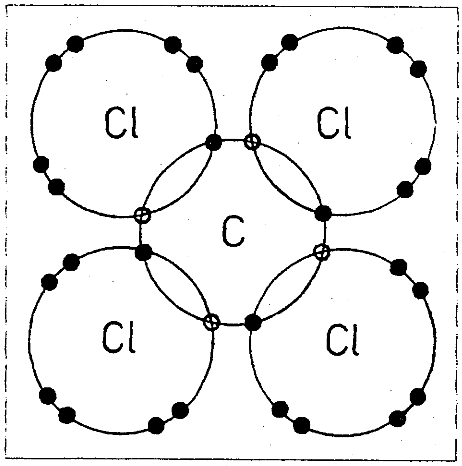
§A30.2.5: Tajinder.

In Tajinder's third interview he attempted to explain the electronic configuration of an oxygen atom in terms of orbital occupation, but was unsure whether there were "two", "eight" or "six" p-orbitals in the atom's outer shell (T3.A336), before settling on "four p orbitals" (T3.A336). Although he recalled there being quantum numbers labelled "l, m and n" he could not explain how the scheme worked, and suggested that for the second shell the principal quantum number would be variously "n minus one ... m, l?" (T3.A366). In his fifth interview Tajinder labelled various orbitals as "$1s^1$" (T5.A175), "1p" (T5.A182), "$1p_x$ orbital" (T5.A192), "$1p_y$ orbital", and "$1p_z$ orbital" (T5.A195). Whereas Tajinder was using designations that defined non-existent orbitals, he later denied the existence of 3s and 4s orbitals, (T5.A288). Later still he referred to an electron in a sodium atom being in a "$3s^1$ orbital" (T5.A459). Tajinder was asked to draw a series of diagrams to represent energy levels, shells and orbitals. When he came to label the diagram 'energy levels in atoms', he referred to a copy of the periodic table, but was still unable to work out the accepted labelling of the levels,

> "I think it goes 1s, 2s, er, 2p, (1s, er, er 1), no you don't have a 1p orbital do yer? No you don't, done that wrong actually. 2p, 3p, 3. Then you have er 3s, then you have 1d, then you have 4p, 4s, 2d."
> T5.B020

§A30.3: Learners' difficulties understanding molecular orbitals.

§A30.3.1: Lovesh.



focal figure 3

In Lovesh's third interview he suggested the electrons shown in focal figure 3 (meant to represent the tetrachloromethane molecule) were in "hybridised orbitals ... [with] sp^3 hybridisation" (L3.A351), i.e. atomic hybrids, whereas from a curriculum science perspective the bonding electrons would be in molecular orbitals. In a concept map drawn as an end-of-year revision exercise Lovesh repeated this view, suggesting that "methane possesses sp^3 hybrid orbitals" and that, "*molecular orbitals are hybrids*, thus the process is called hybridisation" (June 1993).

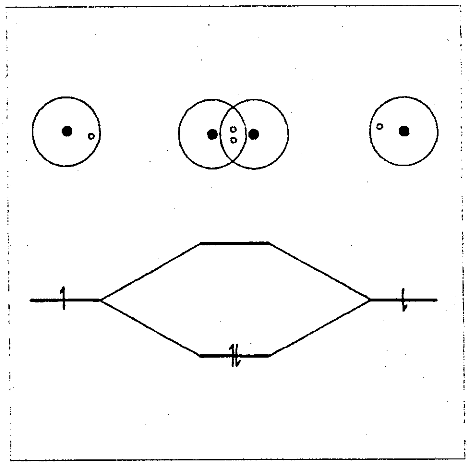
During his second year, in discussion with colearner Umar, Lovesh described how graphite had "got *unpaired p-orbitals*, p-electrons" (LU1.A123) whereas all the electrons are paired, and the p-orbitals had all been 'used' in bonding. In his final interview Lovesh suggested that within the benzene *molecule* a hydrogen atom would have "a s orbital, 1s", and a carbon atom would have "hybridised orbitals", which he thought meant "the 2s and the 2p orbitals have hybridised and become ... hybrid orbitals" (L4.A447). He thought that the carbon also had "a p orbital", and so the hybridisation would be "sp^2" (L4.A447).

§A30.3.2: Debra.

This type of error could occur even when a learner had demonstrated a grasp of the principles involved. So in her third interview Debra thought the bonding electrons in benzene were "in molecular orbitals" (D3.518) *which* were "hybrids"

(D3.520).

However in the simpler example of the hydrogen molecule she had earlier explained how "two atoms are bonded together, and they've both, got one electron before they start and then they form a bonding orbital" (D320).



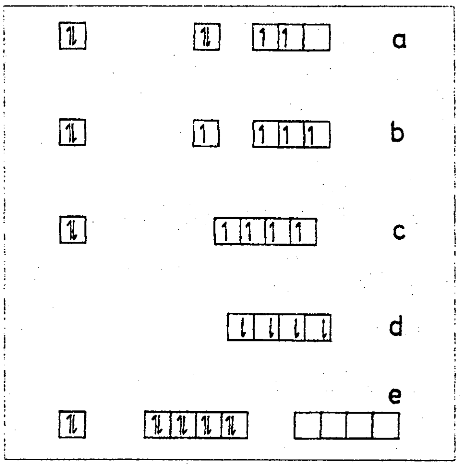
focal figure 18

In focal figure 18 Debra had identified "the energy level of the electron before the bonding" (D3.24) and "the bonding and antibonding energy levels" (D3.28), where "the one where the electrons end up is lower [in energy] than when they started, and the other one's higher, where there's nothing in it" (D3.30).

§A30.3.3: Edward.

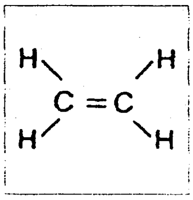
Another example was provided by Edward, who was able to explain the electronic configuration of the carbon atom, so in "the first shell, it's $1s^1$, ... this is the second shell, it's spherical again, ... $2s^1$, $2s^2$, and these are the p-orbitals, they're, they're dumbbell-shaped. And that's erm, px^1 , py^1" (E1.872).

Edward also knew that the carbon atom "could undergo hybridisation, where it, you put energy into the system, in, in the, erm, hope that, you'll get a more stable, resultant, structure" (E1.884). He knew that the energy of an sp^3 hybrid would "be slightly less than the p, but greater than the s" (E1.981) but had "got to be nearer to the p" (E1.983) as "more p[orbital]s are contributing towards the ... average energy" (E1.985) of an sp^3 hybrid, which would consequently have "seventy five percent p quality" (E1.987).

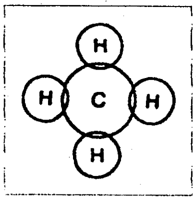


focal figure 30

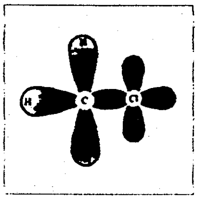
Despite apparently having a good grasp of the notion of hybridisation of atomic orbitals, Edward did not seem to appreciate the formation of molecular orbitals from overlap of atomic orbitals. Focal figure 30, part (e), was intended to include the molecular orbitals formed by the overlap of hybridised carbon atomic orbitals with chlorine orbitals. Edward however misread the bonding molecular orbitals as sp^3 "hybridised orbitals" (E1.1002-4). He ascribed the higher energy (anti-bonding molecular) orbitals as "the orbitals of the chlorine, atoms" (E1.1007), where the electrons had "left their orbitals, to obtain a more stable, er structure" (E1.1007) leaving the chlorine atomic orbitals empty (E1.1010). Edward's interpretation suggested that the hybrid orbitals had shifted their energy level, which he explained in the terms that "they've given out energy" (E1.1015).



triad element 211



triad element 246



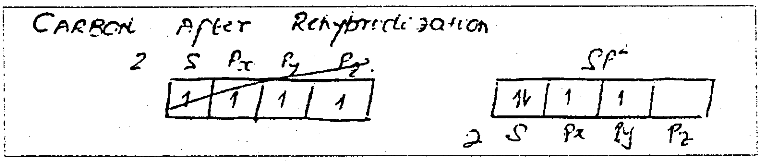
triad element 423

During the first term of the second year of his course Edward undertook the construct repertory test, and construed a number of triad elements showing molecules (211 representing ethene, 246 representing methane, and 423 representing chloromethane) as "hybridised".

§A30.3.4: Kabul.

Some of the difficulties experienced by learners may be illustrated though the example of colearner Kabul. In his fourth interview he discussed the bonding in the oxygen molecule, where he thought that just the 2p orbitals were involved (K4.A430). Kabul explained that a carbon atom also only had two unpaired electrons and it could form "two [bonds], but we can form more if we want" by "hybridising it" (K4.A450). This was because the "2s orbital has got two electrons, so when hybridising it, it can let one of its electrons go into $2p_z$ orbital, and then you have got four" (K4.A450). Kabul knew that when an atom "undergoes hybridisation, ... the s and p orbitals combine together to form ... orbitals of the equal energy level" (K4.A490), although he thought that after hybridisation there would be a decrease in energy, as "2p orbitals are at a higher energy level compared to 2s orbitals, when you combine them, you know, the energy level ... is less than p, energy level of the p, but it is greater than s, ... but overall level is lower" (K4.A474).

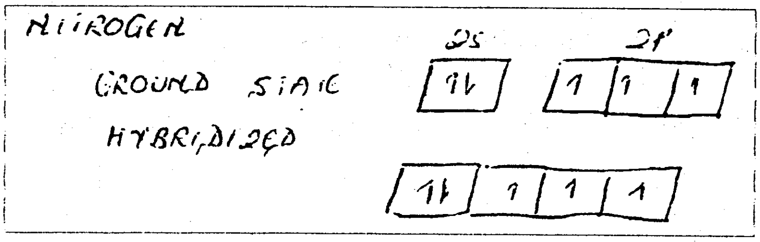
At the end of the first term of his second year Kabul undertook a College test on multiple bonding. In a structured question about the bonding in carbon dioxide Kabul drew the electronic structure of "carbon after rehybridisation" with four boxes joined (the convention for degenerate orbitals).



Kabul's figure for carbon after hybridisation

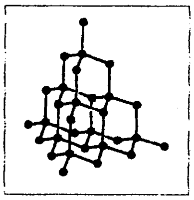
The set of orbitals was labelled sp^2 (i.e. a set of three orbitals), but the four individual boxes were labelled as 's', 'p_x', 'p_y', and 'p_z'. He described the hybridisation needed for bonding as "sp^3 hybridisation for carbon" and "sp^2 hybridisation for oxygen atom", and suggested that "one of the sp^2 hybrids of carbon e.g. $2p_x$ overlaps with one of the sp^2 hybrid of oxygen e.g. $2p_y$" (course assessment response, December 1993). These responses are not only incorrect from the CURRICULUM SCIENCE perspective (with sp hybridisation on the carbon) but contain internal contradictions - the same orbital being described as both p-orbital and hybrid - that make it difficult to produce a consistent interpretation of Kabul's thinking. It seems likely he was himself unsure of a coherent scheme.

At the end of the first term of the second year of his course, Kabul undertook a College test on group 5, and he was able to explain the existence of two chlorides of phosphorus, but only one of nitrogen as "it [nitrogen] has no low lying d-orbitals, to promote electrons during hybridisation" (December 1993). He drew a box diagram to show the appropriate electronic configurations for nitrogen before and after hybridisation,

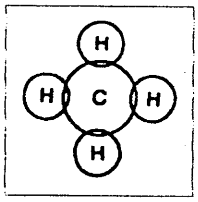


Kabul's figure for nitrogen configurations

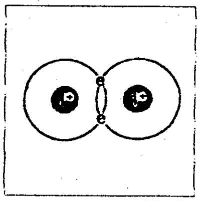
When he undertook the repertory test during the second term of his second year Kabul construed triad elements 145 (showing a tetrahedral arrangement as in diamond) and 246 (showing a methane molecule) as "sp^3 hybridisation", an assignment he confirmed the following week during interview K5 (K5.A331).



triad element 145



triad element 246



triad element 314

This seemed to suggest that Kabul associated the hybridisation *with the molecule*. Kabul was asked more about his understanding of hybridisation during this interview. He thought it was "the orbitals containing unpaired electrons" that were hybridised (K5.A347), although "not always", as "if it is in the same energy level, take p, p orbitals, then all of them can get all hybridised if they *want* to", or "if they are [able to] obtain a stable structure by not hybridising they can just hybridise partially" (K5.A347). The option that occurred "depends [on] what they *want* to form, like ... if they *want* to form [for] example methane, ... they need four bonds, so they form sp^3 hybridisation, when in ethene, for example, they need two, two bonds for hydrogen, and two bonds for carbon so they could undergo sp^2 hybridisation" (K5.A356). (Learners' use of anthropomorphic language is considered in chapter 11.) Kabul initially thought that for forming ammonia there would need to be "sp^3" hybridisation because he thought that would provide "three equal bonds with hydrogen" (K5.A368). Kabul explained that he thought the hybridisation "depends on the number of electrons it has got, you know, in its orbitals, nitrogen has got ... seven electrons, ... if you look at the electronic configuration of nitrogen, that's 1s^2, 2s^2, 2p^3, it's got three unpaired electrons, in its p-orbital you know, and in order to get good overlap, you know, they hybridise it, and they form sp^3 hybridisation" (K5.A375).

Kabul suggested that sp^2 hybridisation would not occur in ammonia,

> "[it] won't form good overlap. ... Because only two of them ... are similar, but the third one [is] not that similar ... [whereas in] sp^3, all three [sic] orbitals are similar."
> K5.A387

At this point Kabul was ***not*** describing a set of three sp^2 hybrids, which would differ only in orientation, as would a set of four sp^3 hybrids. Kabul said that there were "four" orbitals in sp^3 hybridisation, and that "three" of them were similar, where the "fourth one ... goes to the lone pair of electrons" (K5.A392). However, in methane where carbon would "form four equal bonds with hydrogen" the four sp^3 hybrids were "similar" (K5.A398). Kabul appeared to be comparing the nitrogen ***atomic hybrid*** containing the lone pair, with the ***molecular orbitals*** formed from the overlap of the other hybrids with the hydrogen atomic orbitals.

At this point Kabul conceded that he "dunno" why ammonia was not formed with sp^2 hybridisation, and announced he would "think about that" (K5.A404). Although during this section of the interview Kabul seemed to have some grasp of the key points, particularly the requirement "to get good overlap", he also showed some confusion. It would seem he had still not completely separated the concepts of the hybridised atomic orbitals from the molecular orbitals that resulted from overlap: thus the suggestion that one of a set of hybrids would be dissimilar because it contained a lone pair.

§A30.3.5: Kabul.

This issue was further explored later in the fifth interview. During an extended exchange Kabul's belief that the atomic orbitals still exist in molecular species was elicited, and then challenged. Kabul thought that the orbitals present in the hydrogen molecule were "s orbitals, 1s orbitals", none others, "just 1s orbitals" (K5.A420). In methane he thought there would be "1s and p orbitals ... like 2p on carbon, and 1s on hydrogen" (K4.A424). Indeed Kabul suggested that on carbon there would be not one p orbital, but "four, $2p_x$, y and z, ... four [sic]" 2p orbitals (K5.A428). As well as these 2p orbitals, he thought that "there are [other orbitals on carbon] but they don't take part in bonding" (K5.A428).

When Kabul was asked to confirm that he thought that the bonding in triad element 246 [methane] involves a 1s orbital on hydrogen and four 2p orbitals on the carbon, he agreed (K5.A432), but then decided to "change it" as "p_x, p_y, and p_z, that's just three" (K5.A434).

At this point Kabul reintroduced the concept of hybridisation into the conversation, to provide him with a set of four carbon atomic orbitals,

> "[In triad element] 246, you know, s and p both take part in bonding ... I said, you know, p_x, p_y, and p_z, that's just three. ... And I said four, ... so it has also a 2s, orbitals you know, so it can, you know, hybridise 2s with 2p, to form four orbitals, which are you know equal strength like, 2s is at a, you know, lower energy compared to 2p, if they just form bonds, you know, they won't have good overlap. But if they form bonds which ... are in the same energy level then they get good overlap. So they form [from] s and p from carbon and s from hydrogen."
> K5.A434

Here Kabul seems to confuse two aspects of the hybridisation process. The geometry and orientation of four similar sp^3 hybrids makes them suitable for overlap, whereas the similarity of the energy levels of two overlapping atomic orbitals leads to a molecular orbital of significantly lower energy. In other words, the requirement of similar energy applies to a comparison between (in this case) the carbon hybrid and the hydrogen 1s orbital, rather than the set of hybrid orbitals (which will by definition be degenerate). Although Kabul had talked of the overlap involved in forming bonds, he then went on to describe the orbitals present in a methane molecule as "sp orbitals from carbon and ... s orbitals from hydrogen" (K5.A445). By "sp" he meant "s and p orbitals ... [such as] sp^3 hybridisation" (K5.A449).

Kabul thought that the orbitals actually present in carbon in diamond were "1s, 2s, there is, and 2p, but the 1s orbitals present they don't take part in bonding, it's just the 2s and 2p orbitals which take part in bonding" (K5.A458). Kabul suggested there was no hybridisation in this substance (K5.A458), perhaps confusing the element with the state of an isolated atom (see chapter 11 for examples of learners assuming elements exist as isolated atoms), "but when they are to form bonds, then they undergo hy¬ presence of hybridisation, to get good overlap with one another, and they form bonds" (K5.A463).

Then, on direct questioning, Kabul said that there *were* bonds in diamond so it *would* have "hybridised orbitals" and "you can call it sp^3" (K5.A463), where, "they've undergone sp^3 hybridisation, because one of [sic] the 2s orbitals and three p orbitals they all ... combine together to form orbitals which are the same energy level, so you call them sp^3 hybridisation ... or you call [them] sp^3 hybridised orbitals" (K5.A467).

Kabul was presented with a hypothetical commentator who might suggest that there were no 1s orbitals in triad element 314, and no sp^3 hybrids in triad element

246, but he disagreed with both of these suggestions (K5.A480). However he agreed with the suggestion that there was a molecular orbital present in 314, and he said this was "made up of, for example, two atomic orbitals, when they form a bond, the orbitals, you know, combine together to form a molecular orbital" (K5.A487).

In this particular case the molecular orbital was made up from "the two 1s orbitals" (K5.A487). Having recognised the presence of the molecular orbital, Kabul *then* agreed that there were no 1s orbitals in the hydrogen molecule,

I: And someone says to you 'right, aren't any 1s orbitals present in
this molecule, because the 1s orbitals were used to make the molecular
orbital'.
• • [pause, c.2s]
K: Yeah, true.
I: You'd agree with that?
K: Yeah.
I: So are there any ... 1s orbitals present in that molecule?
K: No, no longer.
I: There aren't any more?
K: No.
K5.A494

However, this volte-face did not result in an immediate re-think on the presence of (valence shell) atomic orbitals in the methane molecule. Rather the following extract demonstrates how the significance of the case of hydrogen for the example of methane took some seconds to register (the transition being between the italicised "Yeah" and "No,..."),

I: Same person comes along, and says, 'there aren't any sp^3 hybrid
orbitals in this 246, this methane' What do you think?
K: {chuckles} I disagree.
I: You disagree?
K: Yeah, there are sp^3 hybrids.
I: You think there are?
K: *Yeah*.
I: sp^3 hybridised atomic orbitals?
K: *No*, but they've combined with hydrogen,
I: Mm.
K: actually, to form molecular orbitals,
I: Mm.
K: so, {snorts} yeah if you, yeah there aren't any sp^3.
I: There aren't any?
K: No.
K5.A497

When the third triad element is considered, Kabul accepts the proposition immediately,

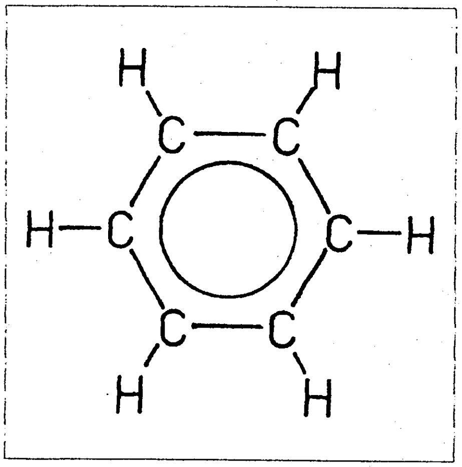
I: Okay, what about in 145, are there any sp^3 hybridised orbitals
there?
K: No, all molecular orbitals.
K5.A502

This section of the interview has been discussed at some length as it demonstrates that Kabul had both the necessary knowledge, and the competence, to discuss the orbitals present in hydrogen, diamond and methane from a molecular orbital perspective - one might say such a description was within his zone of proximal development (see chapter 2, §2.2.2) - but that he spontaneously tended to think of the molecules in terms of the atomic orbitals present before bonding.

§A30.4: Learners' difficulties with understanding resonance.

§A30.4.1: Annie.

Although Annie referred in her third interview to "the double bond and the single bond and then ... the bond moves" she recognised that this was "a simplistic way of looking at" benzene (A3.233).



focal figure 12

Annie was aware that the canonical forms were not accurate representations of the structure of benzene,

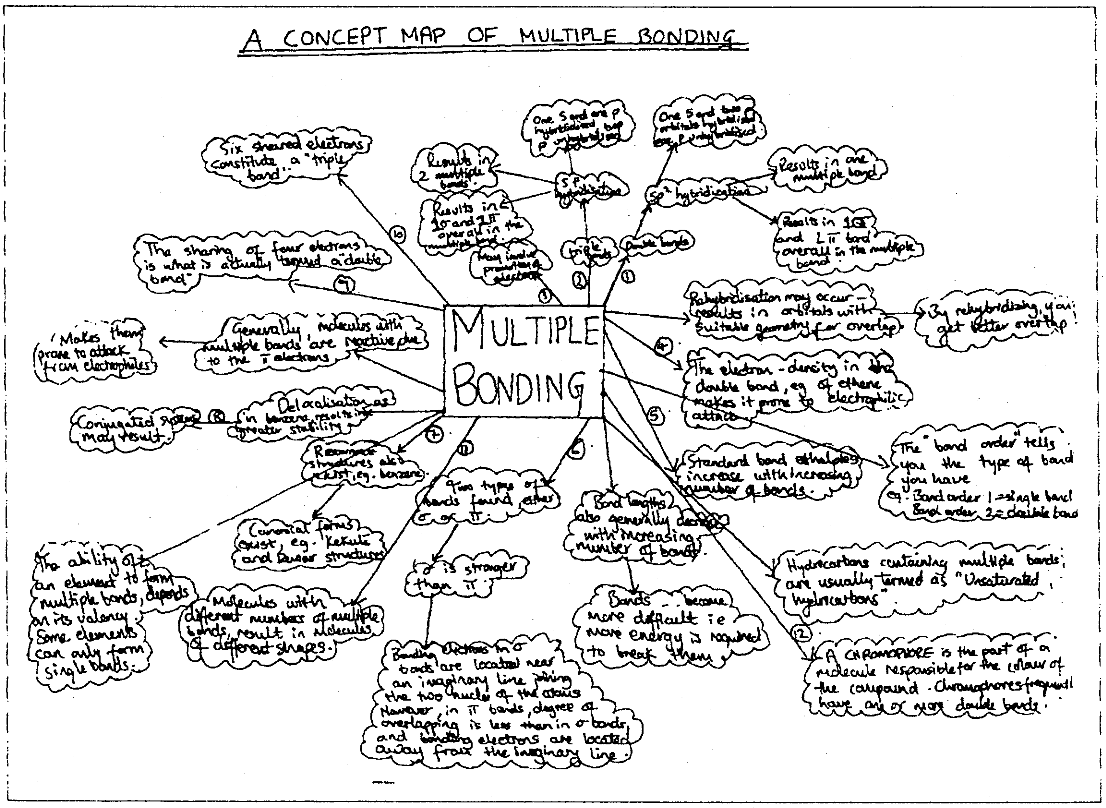
> "[it is called] delocalisation. It's a ... conjugated bond system, or something. I think I can spell it - whether I can pronounce it though! {Laughs} ... you can draw like canonical forms of benzene ... [and] it just shows where the bonds could lie, but whether, they don't really exist, it's sort of something that scientist has in their minds to show, to explain something. So sort of three out of the six could be in one position or they could be, in the sort of reverse, although, sort of, I don't know if I should say in nature, they don't actually perform that way"
> A3.263-9

However, Annie did not seem to consider the role of molecular orbitals, and was limited to discussing benzene in valence bond terms,

> "you've got delocalised electrons in a benzene, benzene molecule, er, the electrons aren't, they're sort of distributing throughout the, throughout the sort of complex, ... because you've got such a, a, such a structure with benzene whereby *you haven't got single bonds all the way around, you've got to have three double bonds out of six*, they sort of delocalise so that everything's sort of, equal in the end"
> A3.231

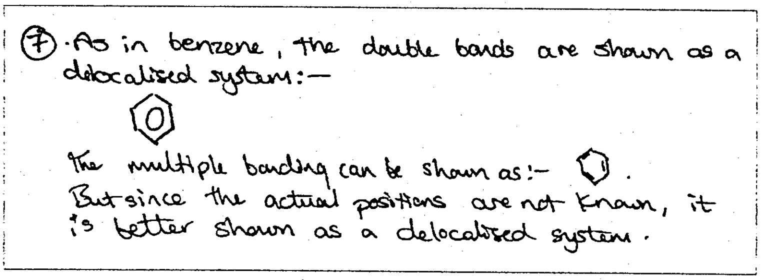
§A30.4.2: Quorat.

During Quorat's second year she prepared a concept map for 'multiple bonding' as a revision exercise. This map (reproduced below) included a reference to 'resonance', that "resonance structures also exist, eg. benzene." and that "canonical forms exist, eg. Kekulé and Dewar structures" (proposition 7 on the map).



Quorat's concept map on multiple bonding, November 1993

However her explanatory notes suggested that Quorat construed 'resonance' as a device for overcoming ignorance about which bonds were double and which were single, rather than as a means of representing bonds with non-integral bond order, e.g. those which were between single and double bonds,



⑦ · As in benzene, the double bonds are shown as a delocalised system:—

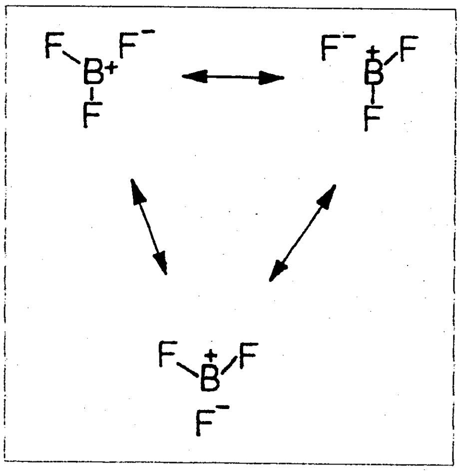
The multiple bonding can be shown as:- .
But since the actual positions are not known, it is better shown as a delocalised system.

detail from notes for concept map, November 1993

("The multiple bonding can be shown as [alternating single and double bonds.] But since the actual positions are not known, it is better shown as a delocalised system.")

§A30.4.3: Kabul.

In Kabul's fourth interview, he was asked to consider the diagram of resonance in BF_3 (focal figure 14) which he thought showed that "sometimes, one of, this fluoride ion is negative, so sometimes this fluoride, another fluoride ion can be negative. It shows like resonance" (K4.B381).



focal figure 14

The CURRICULUM SCIENCE meaning of the term resonance would be that all three of the bonds were something in between ionic and covalent, but further questioning suggested that this was not what Kabul meant,

I: Ah. So, if you, if you could actually freeze some of this, and look at it in an instant in time,
K: Yeah.
I: what kind of bonds would you find?
K: Covalent.
I: All three?
K: No, two of them, one of them probably ionic.
I: And which one would be ionic?
• • • • [pause, c.4s]
K: Like over here [indicating one of the canonical forms] if you freeze it, > then this'll be ionic. >
I: < {laughs} < That one will be ionic in that one?
K: Yeah.
I: So if you looked at it very closely, would you see two different types of bonds [sic] present?
K: No, not really.
I: No?
K: No.
...
I: If you could tell where the electrons were,
K: Yeah.
I: if you could actually see where the electrons were, would you be able to tell the type of bonds present?
K: Yeah.
I: And what would you expect to find?
K: Probably covalent.
I: All three of them?
K: Two of them.
I: Two of them?
K: Yeah.
I: And one?
•
K: Ionic.
I: And which one would be ionic?
K: The one you know, like example this [indicating one of the canonical forms] > if you freeze, >
I: < {laughs} <
K: freeze it, this one.
I: Okay.
K4.B381

Although Kabul referred to resonance, his spontaneous expectation was that the bonds would be covalent (K4.B377), and his interpretation of the figure was that individual bonds would at any one time be covalent or ionic. In his final interview Kabul thought that the figure represented "resonance" which meant "it can exist in either [sic] form. It can be either of them, at any time" (K6.B084). Kabul thought that the diagram probably meant that "it's bonded covalently with two and ionically with one" (K6.B096). Changing between the the different forms required the "atom" to "just flick around" (K6.B102). So even near the end of his course Kabul did not consider the intended meaning of the resonance.

This particular example, representing polar bonds as a resonance, may demonstrate something more than a difficulty with a molecular orbital description, as it will be suggested in chapter 11 that learners in this study commonly showed some reluctance to label bonding as intermediate to ionic and covalent.

Appendix 31.

Evidence of learners' alternative ideas in electrostatics.

§A31.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 10 develops one of the main themes introduced in chapter 6, i.e. that leaners may have alternative notions to the CURRICULUM SCIENCE which is assumed background knowledge for understanding chemical bonding.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 10.

§A31.1: Ignorance of electrostatic forces.

§A31.1.1: Annie.

Although Annie saw charge as a deviation from noble gas electronic structure, and therefore classed neutral atoms as charged, she believed that there would be a force between two particles that were charged in her scheme. For example, a sodium atom and a chlorine atom "would probably get held together by just forces" (A1.256). The force was, "the attraction from the plus to the minus because like *chlorine's minus an electron* and *sodium is over an electron*" (A1.260).

Annie explained that,

A: Sodium has like one extra electron, 'cause it has like an extra electron in its outer shell, and chlorine has seven electrons in its outer shell so its minus an electron so by sort of exchanging, the sodium combining with the chlorine just by force pulls they would hold together.
I: You say by exchanging, did you say?
A: Yeah by, well just the attraction in them.
...
I: And that is what holds them together the fact that this is one short,
A: yeah,
I: one over > and one short. >
A: < One over, and that one's < one short.
I: So the plus means one electron more than an outer, the full shell,
A: yeah
I: and the minus means one electron
A: minus
I: less than an outer shell,
A: yeah,
I: and that's what holds them together?
A: Yeah.
A1.262

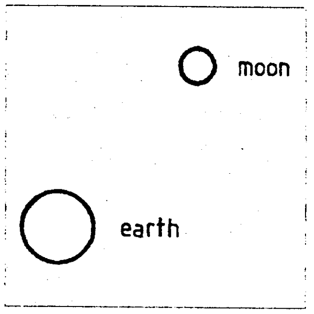
The force was seen to be a direct consequence of the deviation from a stable electronic structure, that is the lack of, or abundance of, electrons in her terms,

I: Yeah, do you want to have look at number 7 then. ...any idea what this is meant to be?
•••• [pause, c.4s]
A: Oh, er, I can visualise the work. It's the attraction, of two hydrogen atoms. I can't think what it's called. Sort of, you've got two electrons, two atoms, and it's the way that the, the force pulls them together. And the sizes of them.
I: Okay, so what kind of force is it that pulls them together?
A: Their, their electrons, the lack of, lack of them and abundance of them.
I: Right and in this case, hydrogen, is it a case of lack of electrons, or abundance of electrons?
A: Lack of them.
I: So they, so each atom is lacking how many electrons?
A: One.
I: One. So that lacking of electrons pulls them together because they've got a desire > to make > up the full numbers?
A: < To make, < yeah.
I: Is that, is that right?
A: Yeah.
A1.304

So for Annie it was not electrostatic charges, but 'deviation charges' which gave rise to a force.

§A31.1.2: Kabul.

Kabul did not seem to commence his study of chemistry with a concept of potential energy, although later he seemed to incorporate this notion into his concept of force. Focal figure 62 was meant to represent the earth and the moon.



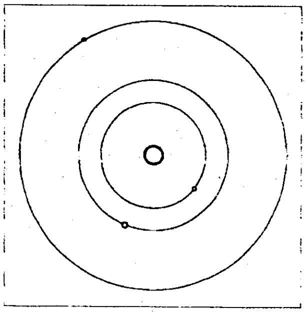
focal figure 62

Kabul thought that "theoretically" there would not be any force in the situation represented,

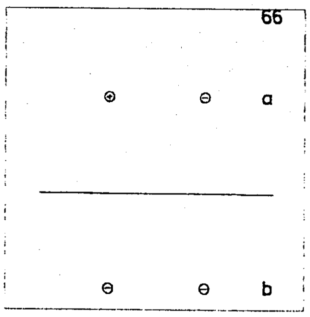
> "but practically yes, because the moon and the earth, you know, they just rotate around each other. So if there was no force, then the moon would just separate from the earth"
> K3.B030

The force would be "attraction force", and Kabul thought it was "centripetal force ... probably" (K3.B035). Kabul recognised that there would be "kinetic" energy in the system, but no other type (K3.B045), that is he did not recognise any potential energy in this situation.

Focal figure 63 represented a simple solar system, where Kabul thought that the only energy present in the system was "kinetic energy" "located on the planets" (K3.B109). The sun did not have any kinetic energy, and there was no other kind of energy present (K3.B114). However, at one point in this interview Kabul appeared to conflate the concepts of the force between two charges and a tacit appreciation of electrical potential energy.



focal figure 63

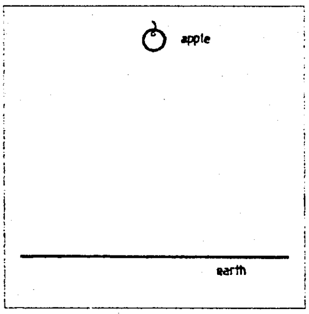


focal figure 66

Kabul was asked to compare the size of the repulsive force in 66b with the attractive force in 66a, and he suggested that the force in b would be "less ... because, after some time you know, once they've repelled each other, there won't be anything" (K3.B209). As the two ions moved further apart the force would get "smaller", whereas in 66a as the charges moved together the force "gets bigger"(K3.B219).

§A31.1.3: Tajinder

In chapter 10 (§10.1.2) it is suggested that Tajinder did recognise potential energy from early in his course, but associated this with one body (e.g. a falling apple) rather than an interactions between bodies.



focal figure 55

In Tajinder's second interview he discussed focal figure 55, and he was aware the apple had "potential energy", which he explained as,

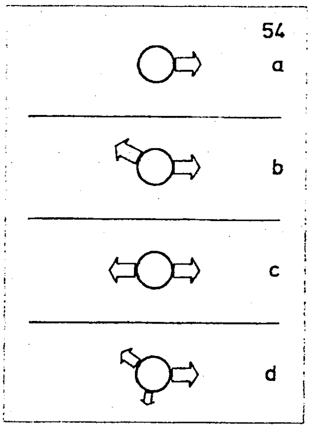
> "potential energy is like stored energy in a certain object and the higher you raise it, the more potential energy it has. And when you drop it, it releases the potential energy into kinetic energy"
> T2.B116

Although Tajinder thought there was a force on the Earth pulling it upwards, he was not sure if *it* had any potential energy "because it's not likely to fall back down again ... it's like it's level. It's not really moving upwards or downwards, any like great distance' (T2.B116). So for Tajinder potential energy was not related to the system of interacting bodies (apple-earth), but to an individual body (the apple). Further the potential energy was not associated with configuration per se: Tajinder only recognised the potential energy when it was converted due to movement.

§A31.2: Newtonian mechanics: inertia, equilibrium and reciprocity.

§A31.2.1: Kabul

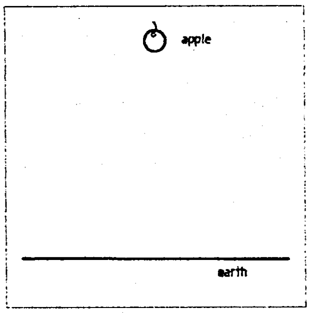
During his third interview Kabul was shown a number of focal figures relating to physical situations, and asked questions about the forces acting.



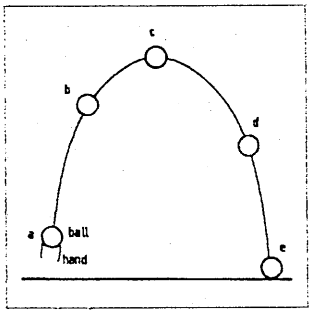
focal figure 54

When he looked at focal figure 54 Kabul suggested that the object in part (c) would not move if the forces were equal as the resultant force was zero, but he would expect the other objects to move (K3.A165) - although he was not sure about part (d) from the limited information in the diagram (K3.A192). If it was not already moving, then the object in part (a) would move to the right (K3.A202). However, Kabul thought that the object would not continue to accelerate, but that the speed "will *settle out on a particular value*, if it's a constant force" (K3.A239). He suggested that if a constant force of 1 Newton was applied *for ever and ever*, indefinitely, "it will just go for *a constant speed*" (K3.A239). Kabul could not suggest what this speed might be (K3.A239), although he thought it would reach 1 ms^{-1}, but not 5 ms^{-1}, (K3.A247). Kabul therefore was not applying a Newtonian framework for force and motion but in contravention of NEWTON-1, and NEWTON-2 appeared to use an impetus-type framework (as discussed in chapter 3, §3.1.3).

Focal figure 55 showed an apple in the air above the ground. Kabul knew it was not possible for an apple to "just hang around", so it would be moving down due to the force of gravity (K3.A313). The only force he believed to be acting in the diagram was "the force of gravity" which was acting "on the apple" due to "the earth", and "towards the earth" (K3.A326). Kabul did not think there was any other force acting on the apple (K3.A332), but (c.f. NEWTON-2) he thought the apple would fall at constant velocity: again he did not expect acceleration (K3.A438).



focal figure 55



focal figure 59

Focal figure 59 showed a projectile at different points on its trajectory after being thrown by hand. Kabul thought the projectile would be subject to the force of gravity at all points, and this would be a constant size, and towards the earth (K3.A515). He thought that at positions (b) and (c) it would also be subject to *a force from the hand*, but that by point (d) "probably it has *used up all its force* in accelerating" (K3.A515). He believed that this force would be at a maximum the instant before the object was thrown, would be slightly less at (b), and less still by (c) (K3.A515). Kabul conceded some of the force might remain by (d), but not enough to overcome gravity (K3.A515). According to Kabul's scheme the resultant force at (a) was upwards, and at (b) it was also upwards although "smaller that [at] (a)" (K3.A515). At point (c) Kabul thought that "probably the resultant force is zero, because at that point it may just stop, you know, for an instant, when it has reached its maximum height" (K3.A548). If the resultant force is zero, things are not moving "for that particular second" (K3.A548). The resultant force at (d) was downwards (K3.A552). The object was stationary at (e), and therefore Kabul did not think any forces were acting (K3.A558). He had suggested there was a force of gravity, and he conceded this was acting, "but [the object is] on the ground, so it's, I think just negligible" (K3.A558).

§A31.2.2: Tajinder

When Tajinder was asked to consider the same diagram of a ball being thrown in the air, he also demonstrated an impetus conception. So according to Tajinder, at point (b) on the diagram, "there's ... a force of gravity, but the, the force of which it was thrown in the air is stronger than the force of gravity, so it travels up, and then when it reaches (c), then it starts falling down" (T2.B197). When specifically asked about the force used to throw the ball, Tajinder seems quite clear that there is only a force acting whilst there is contact between hand and ball,

I: When does the ball experience a force apart from the force of gravity, is there any other force in the diagram at all?
T: Well the force of throwing the ball, up into the air.
I: So how long does that force act?
T: Erm, until it reaches (c), the maximum point on which it travels up.
I: Right so you apply, where do you apply the force?
T: On the ball.
I: So in what part of the diagram?
T: (a)
I: And where does the ball leave the hand?
T: Just after (a).
I: Just after (a). And when does the hand stop applying a force to the ball?
T: Once, once the ball has left the hand completely, it's not touching the hand.
I: So is the is the hand applying a force to the ball at (b)?
T: Erm, no.
T2.B220

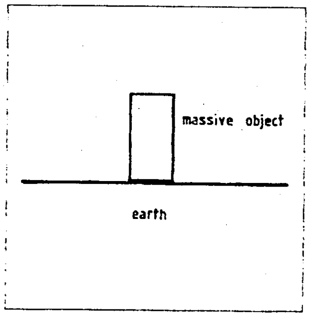
Despite this, Tajinder still sees 'c' as a point where force, rather than momentum, is momentarily zero,

> "the force that it gained from being thrown up in the air, is like erm cancelled out by the force of gravity. And then that's why it comes back down to earth because erm, the force applied by the hand, just sort of, goes back down. I don't know what, erm, what word it is, but then the force of gravity takes over and it brings it back down to earth."
> T2.B220

§A31.3: Equilibrium.

§A31.3.1: Kabul, Quorat, Tajinder.

In chapter 10 (§10.2.2) it is suggested that when colearners were shown diagrams of stable systems (objects stationary on the ground, or on a table) they did not always recognise that there was an equilibrium of forces acting.



focal figure 56

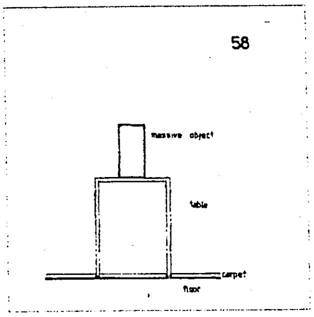
Focal figure 56 showed a 'massive object' on the earth. In his third interview Kabul thought the "force of gravity" was acting "on the massive object" "towards the earth" (K3.A337), but this downwards force was the only force acting on the stationary object (K3.A354), so it was stable although acted upon by a single force.

Similarly, in her second interview, Quorat suggested that the forces acting were not balanced, rather, "they aren't equal, but because it's already down there, it can't go any further" (Q2.A436).

She reiterated that "they aren't equal, the forces aren't equal" (Q2.A436), and explained that "the forces aren't equal, no, the attraction of the earth is going to be bigger because if the forces were equal then, if the forces were equal then the massive object would float away" (Q2.A443). When Tajinder considered focal figure 56 he also identified the presence of "the, force of gravity ... pulling the massive object down" and knew that "there must be a force also acting up on it, from the Earth. On the massive object. ... Because if there was not a force acting-up, the force of gravity would just take it down, straight through, so there must be a force holding it up. So it *balances* out" (T2.B148). However when he was asked which force was larger, he did not immediately see what was needed for the forces to "balance out",

I: Which is bigger?
T: The force pulling it down.
I: So why doesn't it move down then?
• •
T: Erm, because that's where it cancels out with the force pulling it up.
I: Ah, so which is bigger, the force pulling it down, or the force pushing it up?
T: Equal.
I: They're equal are they? Okay.
T: {laughs} Got there in the end.
T2.B148

(This sequence is similar to one reproduced from Kabul's fourth interview below, §A31.3.3), where despite accepting balanced forces, the colearner then suggests which of a pair of forces is larger!)



focal figure 58

Focal figure 58 showed a more complex situation. Here Kabul thought that the force of gravity would act on both the massive object, and the table: this was the same force, and would be the same size, and would act towards the floor in both cases (K3.A443). This was the only force acting on the massive object, but the table was also subjected to a force from the massive object, also acting toward the floor (K3.A443). So according to Kabul's analysis, neither the table nor the massive object were moving, although both were subjected only to downward forces.

When he was asked why the massive object did not fall downwards Kabul replied that is was "being supported by the table", although it would seem he did not consider this support as an instance of a force (K3.A457). He thought that the table was being pulled down by the force of gravity, but does not move downwards as it was already down, that is it had reached its minimum level, the earth, and could not go any further (K3.A475). At this point, for the first time, Kabul suggested that there was an upwards force - that as the earth supports us "it acts its force upwards", and that the table was also "acting its force upwards" (K3.A483). However, in applying this conception Kabul made another NEWTON-1 ERROR, that the upwards force provided by the table was *greater than* the force of the massive object and the force of gravity (K3.A483). Kabul thought that the massive object was subject to the downwards force of gravity, and a greater upwards force from the table, and this meant it would not move (K3.A487). When he was asked why a greater upwards did not lead to a movement in that direction, Kabul did not seem to be able to consider balanced forces, responding that "if the force of gravity is bigger, then you would ask 'why doesn't it go downwards?'" (K3.A499).

§A31.3.2: Edward, Jagdish, Kabul, Lovesh, Quorat, Tajinder.

In the hydrogen molecule Edward thought "the, attraction for shared electrons is *greater than* the repulsion of the nucleuses [sic]" (E1.165). He thought the attractions must be stronger than the repulsions (E1.173), otherwise "they would exist as ... atoms, not as molecules" (E1.175).

When considering the hydrogen molecule Jagdish described how "this nucleus is attracting this electron and that electron, and that nucleus is attracting this one and that one as well" (J3.A535). There were repulsions "between two electrons", but she thought that "the attractions" were stronger (J3.A538). There was also "a slight repulsion" between the two nuclei, but "in between the nuclei you've got the electrons, ... electron density ... [which was] just going to act as a barrier between the two, nuclei" (J3.B046). Jagdish reiterated once more that "the attractions" were strongest (J3.B046).

In Kabul's fourth interview he suggested the hydrogen molecule would not fall apart because the electrons were attracted to both nuclei (K4.A243). He thought that the electrons and the nuclei also experienced repulsion (K4.A250), but "the attractions pulling them together" were stronger (K4.A253). Kabul offered an explanation of why this should be,

> "each nucleus is attracted to a cloud of two [electrons] ... so it tends to, you know, *the attraction seems much more greater than the repulsion*. The repulsion between two electrons, you know, erm, how can I put this, yeah, each nucleus is attracted to a cloud of two electrons, so *the attraction between them is greater than the repulsion* between two electrons."
> K4.A255

It was pointed out to Kabul that he should also take into account the repulsion between the two nuclei, but he still thought that "the attraction between the nucleus and the cloud of two electrons is *greater than* the repulsion between two electrons and the repulsion between two nuclei" (K4.A266).

In an interview near the end of the first year of Lovesh's course he suggested that in the hydrogen molecule there was "an attraction between the electrons and the nucleus, nuclei of each atom, each nucleus" and "there's repulsion between the nuclei, and [between] the electrons" (L3.247). When he was first asked, he suggested that "the attractions" were largest, but when he explained the molecule does not coalesce "because the nuclei repel each other", he then decided that "they're both the same, that's, that's where it, the at¬ the molecule's in equilibrium" (L3.A247). However in an interview near the end of his course Lovesh had reverted to his earlier opinion that "the attractions" were largest, "because it's together, if it wasn't together that means they repel each other and they don't *want* to come together, and that force is *greater*" (L4.A189).

In Quorat's first interview she explained that in a stable molecule there would be "more force pulling it together" (Q1.A199). Her reasoning was that "there's nothing else that's like trying to pull it, pull it apart, because the electrons are attracted to the nucleus, so it's obviously being held together. And the nucleuses [sic] are attracted by the electrons" (Q1.A199). So Quorat thought that "the attractions" would be stronger than the repulsions (Q1.A199).

In his first interview Tajinder had initially suggested an imbalance of forces. Only when he was asked about the consequences of his response did he realise the forces acting in the molecule were in equilibrium,

T: I think these two would repel more than the attraction of these.
I: So the repulsions would be stronger, > would it [sic]? >
T: < In this case. <
I: So does the molecule fly apart?
T: No.
I: Why not?
• • • • • • • • • • [pause, c.10s]
T: Ah no, then, then, the attraction and repulsion would be the same.
T1.B294

§A31.3.3: Kabul.

The tendency to perceive unbalanced forces comes through in two of the examples given above from Kabul's fourth interview. As reported above, when Kabul was discussing focal figure 5, he thought "the forces of attraction is [sic] greater" (K4.A535). However in response to questioning he changed this position,

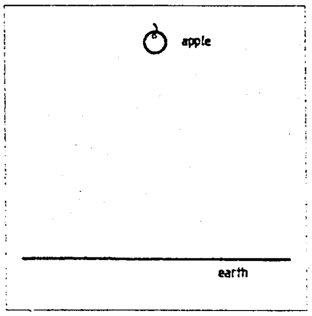
I: So which do you think is the strongest, which is the largest, the er forces of attraction, or the forces of repulsion?
K: I think the forces of attraction is [sic] greater.
I: Yeah?
K: Yeah.
I: What stops, erm, the crystal just falling apart?
• • • [pause of approx. 3 seconds]
K: The forces of attraction.
I: Right, what stops the crystal sort of being compressed closer together, and squeezing up together?
K: The forces of repulsion.
I: Right, which are strongest in this diagram?
• • • • • • [pause, c.6s]
K: E:m. Both have you know, balanced out themselves.
I: So they've balanced them out, have they?
K: Yeah.
I: So there's not over, an overall force pulling the ions closer, or pushing them further apart?
K: No.
K4.A535

However, Kabul did not transfer this argument to the metallic case, so when he was then asked about focal figure 6, Kabul suggested "the attraction is greater" than the repulsions (K4.A559). Again under direct questioning he changes his mind, but nevertheless Kabul suggests an unbalanced force *despite* the earlier ionic example, ***and*** being provided with the scaffolding of questions which lead to him suggesting the forces balance,

I: Do you think that's a stable sort of structure?
K: Yeah.
I: Erm. You don't think particles fall off?
K: No.
I: Why don't they fall off?
...
I: What stops them falling off?
• • • [pause, c.3s]
K: The force of attraction.
I: Right, okay.
I: Do you think it's likely to, erm, to sort of crumble in on itself, and get smaller?
K: No.
I: Why not?
K: The force of repulsion.
I: Ah, I thought there were forces of attraction as well?
K: Yeah, but they just balance out ....
I: Oh, they're balanced out are they?
K: Yeah.
I: So which are bigger, the force of attraction or the forces of repulsion?
• •
K: *The forces of attraction, otherwise they would just fall off.*
I: Right, so if the forces of attraction are bigger, does that mean it gets attracted closer together?
K: Yeah, but at the same time they're they're repelled, you know, so get an overall, an overall balance.
I: Overall balance, so which is bigger?
K: It's the same.
K4.A562

§A31.3.4: Quorat.

In chapter 10 (§10.2.3) it is suggested that another type of error that some colearners made during the study was to consider an equilibrium of forces possible when two forces *acting on different bodies* were equal.



focal figure 55

In Quorat's second interview, it was suggested to her that in focal figure 55 the two forces she identified as "the attraction of the earth to apple, and the apple to earth" (Q2.A427) were equal. Quorat thought "that's not possible, because if that was the case, apple would stay where it was" (Q2.A430), i.e. the apple would not move because forces (acting on different bodies) cancelled out.

§A31.3.5: Tajinder.

In Tajinder's second interview, as well as gravitational force pulling the apple downwards, Tajinder also recognised "there must be a force" on the Earth acting "upwards". Although he did not know what this was due to, he believed it "must be opposite to force of gravity" because "everything would like just collapse inwards if the force of gravity was that strong" (T2.B148). In effect Tajinder was suggesting there was some sort of equilibrium,

I: Oh I see, so if all there was in the universe was the force of gravity pulling things together, the whole universe would disappear into a point?
T: Yeah.
I: It would, wouldn't it? Yeah, that's perfectly true. And that doesn't happen in your experience?
T: {laughing} No, it doesn't.
I: Not yet anyway.
T: {laughs}
T2.B110

Tajinder did not seem to be aware that the possibility of an eventual universal 'big crunch' is actually one of the options under active consideration in cosmology. More significantly Tajinder appeared to be suggesting that an equilibrium could be reached by oppositely directed forces acting on *different* bodies.

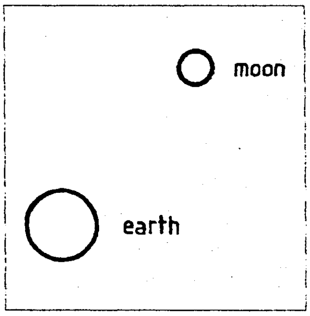
§A31.3.6: Tajinder.

Tajinder's analysis of focal figure 62, showing the earth-moon system, revealed similar thinking, in that Tajinder suggested a type of equilibrium although there was only one force acting on each body,

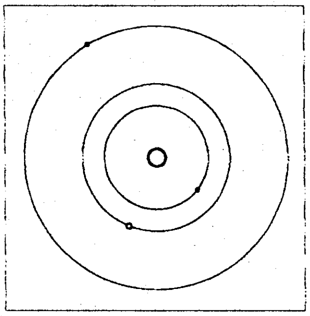
T: ... there's a gravitational force from the earth which is holding the moon, in its position, from that distance away from the earth, and there's also a force from the moon which is repelling erm the earth away from itself, so it doesn't, so they don't like come and collide with one another.
I: So let's see if I got this right, the earth attracts the moon,
T: Yeah.
I: but the moon ... repels the earth.
T: Yeah, to a certain extent.
I: And the overall result of that is?
T: Er, the moon stays where it is, in, the distance, > away from the earth. >
I: < And the earth < as well stays where it is, does it?
T: Er, yeah.
T2.B344

Tajinder's error here is based in assigning 'action-reaction' forces incorrectly (a point discussed below.) However, further discussion revealed that Tajinder appeared to accept a kind of equilibrium in such a system, even when the forces were not of equal magnitude,

I: What about if the moon was bigger than the earth then?
T: Yeah, erm.
• •
T: Well I would then, ... the force of the moon repelling the earth would be larger than the attraction, so it would like float away.
I: Indefinitely, keep going for ever?
• • • • • • • • • [pause, c.9s]
T: Er, dunno, I think they'd be an equilibrium.
T2.B374



focal figure 62



focal figure 63

When Tajinder considered focal figure 63, his analysis of the simple solar system represented included equal forces, as "well when they get to their certain, their sort of er orbits, orbitals [sic], then I think the forces would be equal between them" (T2.B410).

However, this was a balance between an attraction *on the planet from the sun*, and a repulsion *from the planets to the sun*,

T: [The sun] attracts all three of [the planets].
...
I: Would the sun itself experience any force?
• • • [pause, c.3s]
T: The force of the planets repelling towards it.
...
T: Er, well when they get to their certain, their sort of er orbits, orbitals, then I think the forces would be equal between them.
I: Right, so if we take the innermost,
T: Yeah.
I: planet. That's attracted by the sun to a certain extent,
T: Yeah.
I: And it repels the sun to the same extent, does it?
T: Yeah.
I: And that would be true for all three of them?
T: Yeah.
T2.B410

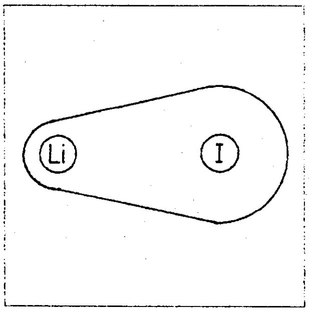
It is difficult to see how this could be true for all three planets in view of Tajinder's suggestion for how the forces between planet and sun vary with separation,

T: It attracts all three of them.
I: Do you think it will attract all three equally.
T: Erm, no.
I: Which do you think it will attract the largest [sic], any idea?
• • [pause, c.2s]
T: Erm. • • • • • • • • • • The one furthest away.
...
I: Which one will it attract the least do you think?
T: The one nearest to it.
I: Would the sun itself experience any force?
• • •
T: The force of the planets repelling towards it.
...
I: Which would repel the sun the most?
T: The one, - erm - the one nearest to it.
I: Right, okay. Which planet did you say was attracted most by the sun?
T: The one furthest away.
I: Right, and you think that the force between the sun and the planet, and the planet and the sun, are balanced?
T: Yeah.
T2.B410

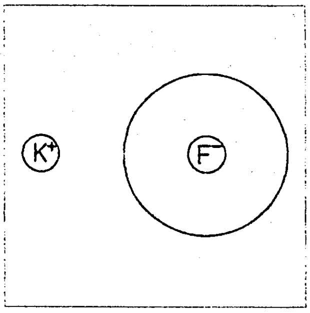
It is not possible to know the extent to which Tajinder's answers were based on long-held views about celestial mechanics rather than an ad hoc creation of an explanatory scheme constructed in the interview context. However, in either case, Tajinder did not seem to realise that his answers contravened fundamental principles of CURRICULUM SCIENCE.

§A31.4: Reciprocity of force.

In chapter 10 (§10.2.4) it is suggested that in this research it was found that learners often referred to forces as though they were a property of one body. This was considered to be significant because it is a perspective which logically allows the learner to make NEWTON-3 ERRORS, and to assume that a particular charge gives rise to a certain amount of force (alternative notions discussed in chapter 10, §10.2.5, §10.3.)



focal figure 8



focal figure 9

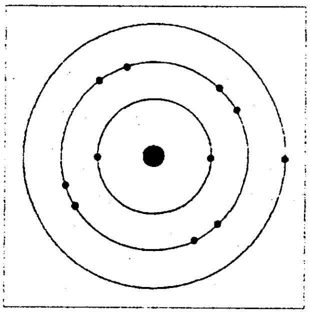
§A31.4.1: Annie.

Annie interpreted diagrams meant to represent the electron density distributions in bonds as force fields. She appeared to have a notion similar to the CURRICULUM SCIENCE concept of *electric field strength*, but not distinguished from force. In the case of focal figure 9 she thought the circle around the fluoride ion was "to show that the, *the force on this wouldn't combine* whereas on, on the, the previous thing [focal figure 8] it's got the, the pull towards either of them, whereas this one the, *the pull is not combining the potassium*" (A2.149.) Annie seems to be imply that the force originates on the fluoride ion, and extends so far, but does not reach the potassium ion.

In her third interview Annie reported that the electrons in the atom are "held together by, erm, sort of, oh, electrostatic *forces coming out from* the ... nucleus of the atom, which pulls the electrons in" (A3.6). For Annie this force originated "*from the nucleus*, erm neutrons, protons in the nucleus, make up a plus charge, which would draw the electrons in, by ... electrostatic forces" (A3.8).

In her final interview Annie made similar comments, suggesting that somehow the force resided in the nucleus,

> "the nucleus *will contain*, will sort, *will contain the force* ... to pull, the electrons towards it ... because the nucleus has the power to draw these electrons in, then *the force I suppose you could say is, either held by the, nucleus* and is sort of dragging electrons towards it *or is held by the ... atoms*, well the electron's always being centred towards the nucleus" A4.26-30



focal figure 1

§A31.4.2: Tajinder.

In his first interview, Tajinder discussed focal figure 1, which represented a sodium atom. Although he was aware that there would be attractions and repulsions operating in such a system, Tajinder referred to a 'central attraction',

I: So, how many attractions are actually there in the diagram, in that atom?
• • [pause, c.2s]
I: How many attractive forces do you reckon they'll be in that diagram?
T: One.
I: Where's that?
T: Er, I don't know, I don't, don't understand what you mean? ... *this is just the central attraction, ... to all the electrons around.*
T1.B220

Tajinder accepted that the electrons attracted the nucleus ("they must do"), but still resisted construing the force acting in terms of interactions between pairs of charged particles,

I: So is there any, is there some sort of force between this nucleus and this electron here?
T: What *just between these two*, and > not say >
I: < Yeah. <
T: Er.
I: Just those two, is there a force between them?
• [pause, c.1s]
I: An attraction?
T: Don't know. Well there is an attraction, there must be a force then.
I: Okay, what about these, the nucleus and this electron?
T: There must be a force there as well.
I: Right, so how many lots of attractive force have we got on that diagram, that's two, how many we got altogether?
• • •
...
T: Eleven. ..., but that might just be cancelled out by one big attraction. Say like.
I: You mean you could consider it to be one big attraction?
T: You could.
T1.B220

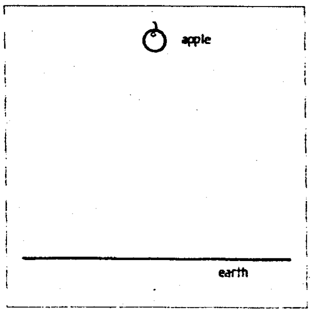
When Tajinder was asked about the repulsions in the system he again did not construe force to be an interaction between two bodies, asking if he should count the repulsion between two electrons twice - once in each direction. My reference to 'the attractions' led to him again suggesting the notion of a single attractive force,

T: Erm, one, so like each electron here is er is er repelling against each other one. ... don't know, could you consider like if this one was repelling against that one?... they would repel, yeah, but I don't know if you count that as two, one against, one repelling against that one, and that one repelling against that one as two, or one? ...
I: That's a good question, that's like the same for the attractions we said there was eleven attractions, didn't we?
T: Yeah.
I: 'Cause the nucleus was attracting eleven electrons?
T: Yeah.
I: But there's also eleven electrons attracting the nucleus, so is that twenty two?
T: Or is that one?
T1.B258

In his fifth interview, when Tajinder was discussing patterns in ionisation energies, he suggested ionisation energy was "to do with ... *how much force the atom has* at attracting that electron ... how strongly for keeping the electron erm, to itself" (T5.A064). This is another example of a force being designated to one part of an interacting system.

§A31.4.3: Kabul, Noor.

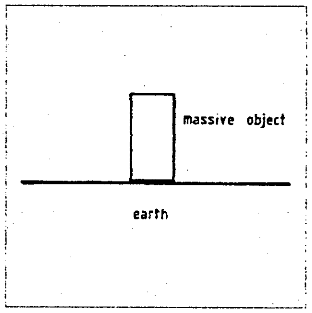
In chapter 10 (§10.4.2) it is suggested that during the study a number of examples of learners not recognising the presence of a 'reaction force' were elicited.



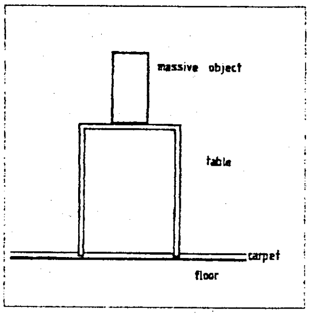
focal figure 55

The only force Kabul believed to be acting in focal figure 55 was "the force of gravity" which was acting "on the apple" due to "the earth", and "towards the earth" (K3.A326). Kabul did not think there was any force acting on the earth (K3.A332): a NEWTON-3 ERROR from a CURRICULUM SCIENCE perspective.

In Noor's second interview she explained that an apple would fall due to gravity. She suggested two explanations of gravity - an "attraction to the sun", and the tendency of everything to fall towards the centre of the earth. Noor thought that gravity only acted on the smaller body, so "the apple gets pulled by the earth, because it's, it's, *it's of a greater mass, it's larger in size* than the apple is" (N2.A520).



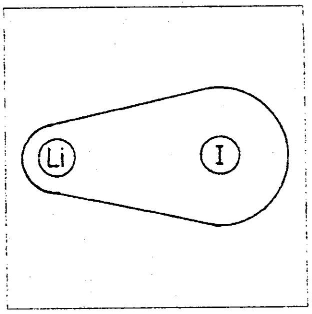
focal figure 56



focal figure 58

§A31.4.4: Kabul.

Kabul thought that in focal figure 56 the "force of gravity" was acting "on the massive object" "towards the earth" (K3.A337), and there was also "the force of the massive object on the earth" acting "towards the earth ... downwards" (K3.A337). He thought that these were the only forces acting, and they were both acting downwards (K3.A354). So according to his analysis the object exerted a downwards force on the earth, but the earth did not exert an upwards force on the object, another NEWTON-3 ERROR. In focal figure 58 Kabul thought that the force of gravity would act on both the massive object, and the table, and would act towards the floor in both cases (K3.A443). This was the only force acting on the massive object, but the table was also subjected to a force from the massive object, also acting toward the floor (K3.A443). Kabul did not think there was any force acting on either the carpet, nor the floor itself (K3.A443). In his analysis then, Kabul had the massive object exert a downwards force on the table, but the table did not exert an upwards force on the massive object - another NEWTON-3 ERROR.



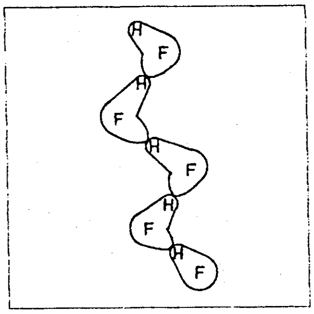
focal figure 8

§A31.4.5: Annie.

In her first interview Annie suggests that in lithium iodide (focal figure 8),

> "lithium has a smaller charge, or smaller pull than the iodine, so the actual shape of it goes in towards. It sort of goes in towards because *it's attracting the lithium, whereas if the lithium were attracting it*, it would be like the reverse picture."
> A1.321

Lithium has a smaller core charge than iodine, and this influences the electron density in the molecule, but Annie appears to be considering attraction between the lithium and iodine. Her analysis contravene's NEWTON-3 where the two interacting species would be subject to the same magnitude force

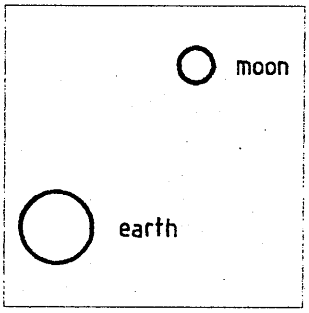


focal figure 11

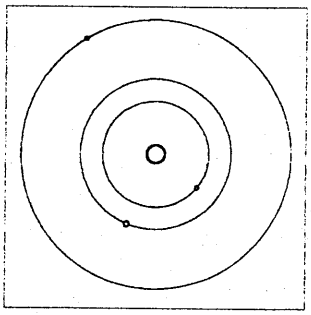
§A31.4.6: Kabul.

In Kabul's final interview, during the last term of his course, he explained why he believed hydrogen bonds formed in hydrogen fluoride (focal figure 11). He said that hydrogen bonding was "an intermolecular bonding, ... between an electronegative element and hydrogen" (K6.A507). Kabul thought such bonding forms "because fluorine is, you know, very electronegative, so it, you know, {laugh} tends to attract further, further electrons from hydrogen, so it just happens" (K6.A520). A bond would form between two hydrogen fluoride molecules that came close because "fluorine attracts electrons from hydrogen ... [and so] this is a polar covalent molecule, so there's a small charge on ... hydrogen atom, it's ∂+, and *fluorine being very electronegative, it tends to attract this plus charge* towards itself" (K6.A524).

From the CURRICULUM SCIENCE perspective to suggest that the *fluorine atom* on one molecule attracts the *hydrogen atom* on another implies that (and is implied by) the *hydrogen atom* on the second molecule attracting the *fluorine atom* on the first. However Kabul thought the hydrogen was "too small to attract that" (K6.A531). The fluorine "attracts a small charge", but the "small charge, ∂H^+, on hydrogen atom, it can't attract, you know, seven electrons towards itself" as "it's just a small charge" (K6.A531). Once again Kabul was making a NEWTON-3 ERROR.



focal figure 62



focal figure 63

§A31.4.7: Tajinder.

In his second interview Tajinder was asked about focal figure 62, which was meant to represent the earth-moon system. He recognised that there would be "gravitational force" (T2.B344) between these two bodies. However, Tajinder explained the stability of the system in terms of a kind of equilibrium, except that the forces that were considered to cancel were acting on different bodies. This scheme was possible because Tajinder had an attraction paired with a repulsion, so that "there's a gravitational force from the earth which is pulling the moon, towards it, ... holding the moon, in its position, ... that distance away from the earth, and there's *also a force from the moon which is repelling erm the earth away from itself*, ... so they don't like come and collide with one another" (T2.B344).

Tajinder applied a similar scheme to the simple solar system represented in focal figure 63, where he thought that the sun would attract the planets, but was being repelled by them, I: Do you think there will be any forces between the sun and any of the planets?

T: Er, yeah... [The sun] attracts all three of them.

...

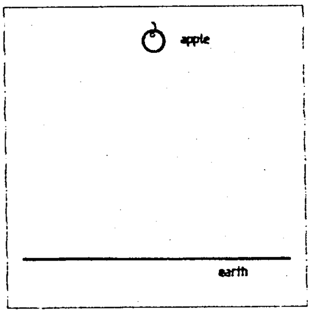
I: Would the sun itself experience any force?

• • •

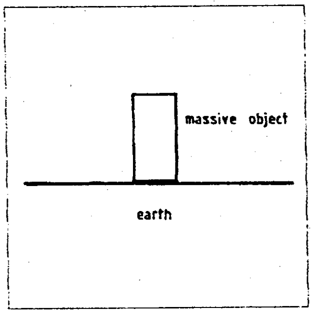
T: The force of the planets repelling towards it.

T2.B410

It seems clear that for Tajinder, at this point in his course, the 'reaction' to an attraction could be a repulsion.



focal figure 55

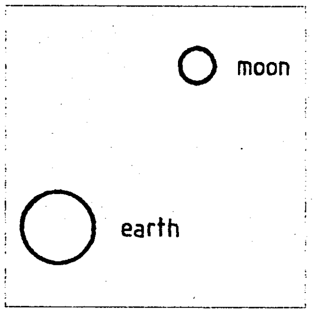


focal figure 56

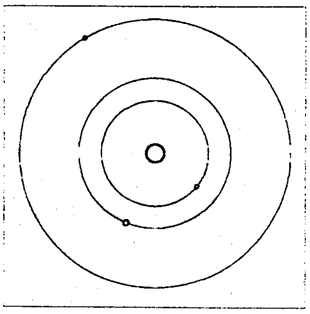
§A31.4.8: Quorat.

In Quorat's second interview, she was asked about the forces acting in a number of situations involving gravitational interactions. In focal figure 55 she initially thought "gravity's going to act downwards and push the apple down towards the earth", but nothing else would experience force (Q2.A378). In focal figure 56 Quorat thought that "gravity is pulling the massive object down towards the earth so it stays, still, stable on the earth, stays still" (Q2.A386). However in this context Quorat thought that there were "two" forces acting, "the earth attracted to the massive object, ... and the attraction of the massive massive object to earth" (Q2.A422), but "the force that earth applies onto the massive object" was the bigger force (Q2.A422). Quorat now reviewed her analysis of focal figure 55 to admit a second force, so there was "the attraction of the earth to apple, and the apple to earth" (Q2.A427). Again she thought that "the one from the earth" had to be larger (Q2.A427) otherwise the "apple would stay where it was" (Q2.A430). However, in focal figure 56 Quorat thought "[the forces] aren't equal, but that because it's already down there, it can't go any further" (Q2.A436). She thought that "the forces aren't equal, no, *the attraction of the earth is going to be bigger* because if the forces were equal then, if the forces were equal then the massive object would float away" (Q2.A443).

So Quorat justified her belief that the force on the smaller object is greater by, in one case, the fact that the object falls and does not stay still, and in the other case, that an object stays still and does not float away.



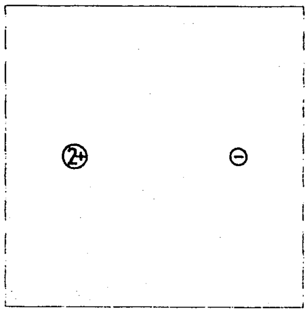
focal figure 62



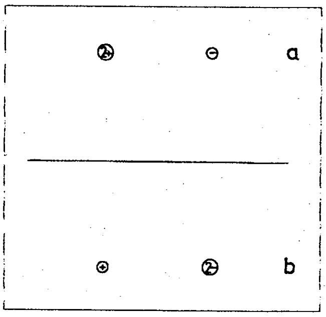
focal figure 63

§A31.4.9: Quorat.

Later in the interview Quorat was asked about the earth and moon (focal figure 62), where she thought that both the earth and moon were "subject to a force, but the moon is subject to *more* force from the earth" (Q2.B113). The earth did not move around the moon, but "the moon's going round the earth" because "the earth is bigger, it's got bigger gravitational attraction" (Q2.B116). In a simple solar system (focal figure 63) Quorat thought that "the sun's attracting all the planets" (Q2.B189), but "because the mass of sun is bigger, it like, it doesn't show any effect of planets", as "the *force* of the sun on the planet is *greater*" (Q2.B224).



focal figure 69b

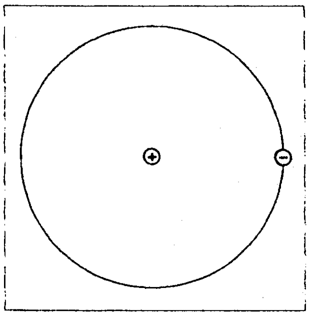


focal figure 70

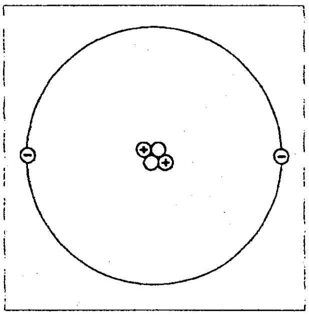
§A31.4.10: Quorat, Tajinder.

Quorat applied similar beliefs to the forces between charged particles. So in focal figure 69b she thought that "the positive one ... has *more force* on the negative charge ... to attract it towards itself", or put another way "the negative charge, [was attracted the most] towards the positive one" (Q2.B395). In focal figure 70a Quorat thought that "the negative charge will experience more force than the positive one" (Q2.B417). Conversely, in focal figure 70b she suggested that "the positive charge will experience more force than the negative one" (Q2.B417)

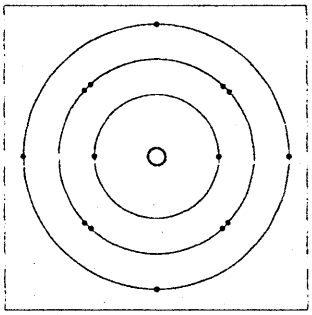
Tajinder also thought the negatively charged particle would experience the most force, and the positively charged particle the least in focal figure 69b (T2.B551), and that in focal figure 70 the negatively charged particle would experience the larger force in part (a), and that the positively charged particle had the larger force on it in part (b) (T2.B562).



focal figure 73



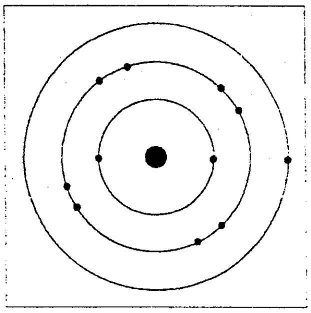
focal figure 74



focal figure 75

§A31.4.11: Quorat, Annie, Jagdish, Kabul, Paminder, Noor.

In focal figure 73, where charges were just signified '+' and '-', Quorat seemed to make additional assumptions in suggesting "the nucleus, as I'll call it, is positive, and the electron, is negative" (Q2.B439), and she thought that "the force on the negative" would be a larger, although she could not give any reason, and admitted that she was not sure. (Q2.B439). Similarly, in focal figure 74 Quorat suggested that "the positive charges in the centre will attract the negative charges" (Q2.B448), and the negative charges would also attract the positives, "*but the positive charges attract the negative charges more*" (Q2.B448). Again in focal figure 75 Quorat thought there was force acting on the nucleus "from the electrons but ...*the force due to the nucleus on the electrons is greater*" (Q2.B474).



focal figure 1

In Annie's final interview she accepted that the atomic nucleus would be attracted towards the electrons as well as vice versa, but she suggested that the force on the nucleus would be less than the force on the electrons. Her reasoning for this seemed to be that the nucleus had a larger charge than an electron, although this was extended to the case of hydrogen, where she believed that the "pull on the electron from the nucleus" (A4.243) was greater than the pull on the nucleus of the electron, as "although they they're of similar charge, it seems to be convention that that's the way that ... the force goes" (A4.245).

In Jagdish's third interview she was discussing the force acting on a sodium atom's electrons, and thought there was also an "electrostatic force" acting on the nucleus but "it's negligible, because the electron has such a small mass" (J3.A335). Similarly, in the case of the hydrogen atom "if you *just* say that the electron is being pulled toward the nucleus, that wouldn't be entirely true because, I think the nucleus is being pulled towards the electron as well, but, *the pull is greater* towards the nucleus because it's so much bigger • than the electron" (J3.A541).

When Kabul discussed focal figure 1 in his fourth interview he at first suggested that he did not think there was any force on the nucleus, due to the electron (K4.A143), but he qualified this, saying that "because there's just one electron, and over here we have, you know, combined about eleven protons, eleven protons pulling an electron, so - the force, *even if there is some force* it's just negligible" (K4.A194).

Kabul explained that "there isn't much [force on the nucleus]. Of course ... it's a negative charge and this is a positive charge, there should be some force but it's, it's negligible" (K4.A198). In the case of a helium ion (He^+) the force "from the nucleus" was "twice" as large (K4.A215), and in the case of the innermost sodium electron the force "from the nucleus" was "ten times" bigger (K4.A219). As Kabul explained later in the interview,

> "In the nucleus there are, • • [for] example in sodium atom, there are 11 protons, so 11 protons are attracting the first nu¬ the first electron, and so the first electron is attracted more, compared to the nucleus being attracted to the electron, know what I mean. Over here [on the electron] there is just a small charge of minus one, *minus one can't attract, you know, plus eleven,* as plus eleven can attract minus one, you see what I mean."
> K6.A544

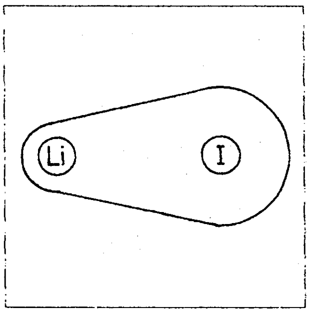
In Paminder's interview near the end of the first year of her course she made a similar point, that "the nucleus is attracting the electron, *more* than the electron is attracting the nucleus, because the nucleus will have a greater charge because it's got eleven protons in it, ... it's got plus eleven, and the electron has got charge of only minus one, so plus eleven is a lot greater than minus one, so" (P3.A248).

In Noor's third interview, near the end of the first year of her course, she also thought "there's a greater force pulling the electron towards the nucleus"

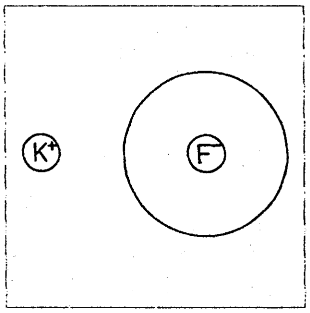
(N3.A264) because,

> "the nucleus is a larger mass than the electron. So this, I mean the sm¬ the electron is quite small, in comparison, so ... *it's not going to have much force*, and so it's not going to be able to pull the nucleus towards it."
> N3.A264

In this utterance Noor implies there is a set amount of force associated with an electron, an apparent reference to a designated force (c.f. appendix 7, §A7.7.3).



focal figure 8



focal figure 9

§A31.4.12: Annie.

Annie had initially suggested that in lithium iodide there was attraction in one direction - iodine attracting lithium. Later she changed her mind, so that "they're both attracting each other but because this one's *got a larger force* then it will pull ... towards the lithium more" (A1.325). In the second interview Annie repeated this position, and gave as part of her reasoning that "the iodine molecule's bigger, than the lithium molecule" (A2.111). In her final interview Annie considered focal figure 9, and recognised that there will be an "electrostatic" (A4.318) force from the potassium ion onto the fluoride ion (A4.316) and also from the fluoride ion onto the potassium ion (A4.320). However, Annie thought that "the strength from the fluorine to the potassium will be far greater, than ... like from the potassium to the fluorine" (A4.324).

§A31.5: The notion of 'conservation of force'.

§A31.5.1: Tajinder.

Tajinder used his CONSERVATION OF FORCE EXPLANATORY PRINCIPLE when he was discussing atomic energy levels during interviews in his first year. In his sixth interview he considered how the energy levels of electrons in the helium atom, and helium cation might compare. The level in the atom would be higher because of the repulsion of the second electron, but Tajinder reached the same conclusion in terms of ***sharing*** the nuclear force. He thought the atomic energy level "would be a little bit above the helium ion, because, erm, in - in the ion, it's, the two proton's are only attracting one electron, but in this one they're they've got two electrons to attract, so therefore like sort of their - their ***their attraction is like spread out over two instead of one***" (T6.A430).

In his seventh interview, Tajinder's notion of force conservation was made explicit. Again the critical comparison was made between the helium atom and the helium ion. Tajinder thought the energy level for the atom would be higher than the ion, as in the ion "the protons only have ... one electron to attract, in helium ion, helium atom they've got two electrons to attract" (T7.A551). In terms of ionisation of the atom, "the amount of energy you need is slightly less than the helium ion" (T7.A551). Tajinder explained this was,

T: Because there's two electrons to attract, rather than one electron to attract.
I: Right, so what are you saying about the amount of force that the nucleus can give out?
T: It's, it's erm, spread over the number of electron there are. That's what I'm saying.
T7.A559

At this point I checked my interpretation of Tajinder's meaning,

I: So if you've got an extra electron, the nucleus can't just give out extra force?
T: Not if the charge hasn't gone up by one.
I: Right, so a certain charge on the nucleus, implies there's a certain amount of force available,
T: Yeah.
I: And if you increase the number of electrons, you therefore ... decrease the amount of force each one gets?
T: Erm, yeah.
I: Kind of 'conservation of force principle'
T: Yeah.
T7.A562

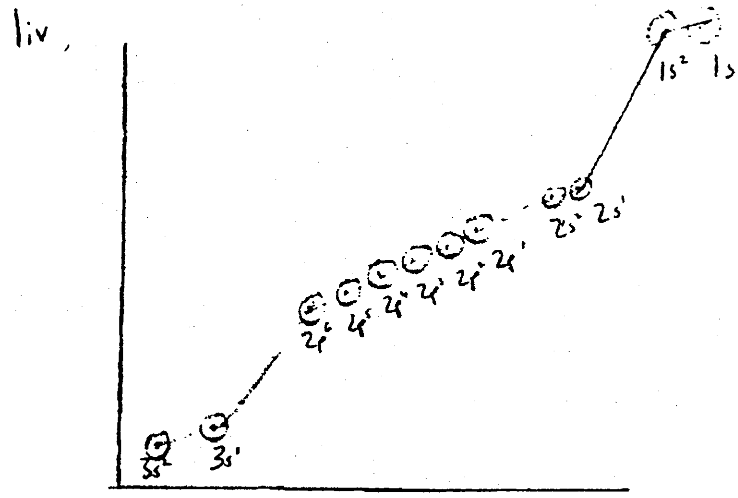
It was explained to Tajinder that force was not conserved in this way, but that the ionisation energy of the atom would be less due to repulsion between the two electrons. Tajinder accepted this at the time, but later, when the second and third ionisations of lithium were considered, his initial tendency was still to think in terms of force conservation,

T: ... there would be more attraction so the force you need is greater, so it would be below here [on an energy level diagram].
I: Right, why would there be more attraction?
T: Oh yeah, er, ... that's what I said wrong last time as well.
I: Would there be more attraction because you're not having to use up some of this charge > to attract that? >
T: < {sighing} Oh yeah. > Yeah that's what I thought.
I: Is that what you were thinking?
T: Yeah, but that's wrong though isn't it? Erm, [the correct answer is] because, because of the repulsion between these two electrons. That's why.

T7.B428

§A31.5.2: Umar.

Umar also seemed to apply the CONSERVATION OF FORCE EXPLANATORY PRINCIPLE in his explanations of ionisation energy throughout his course. So Umar's response to an assessment question on ionisation energies shortly after being taught about the topic suggested he also thought in terms of nuclear charge being shared between the electrons. Umar had drawn an appropriate diagram for the successive ionisations of magnesium,



electronic configuration = 2.8.2, atomic no. = 12

$1s^2\ 2s^2\ 2p^6\ 3s^2$

Umar's diagram for assessment question on successive ionisation of magnesium

Umar's explanation of this pattern included both points which would be judged valid from a CURRICULUM SCIENCE perspective, and several references to the core charge being shared amongst the electrons present. In all there are four references to the increasing share of core charge that a smaller number of electrons experience. In his third interview for the research (near the end of the first year of his course), Umar suggested that, in an anion, nuclear charge was shared over the electrons present, so that "an anion which is negative has got like less protons in the nucleus but more electrons so its each electron's got less charge on it overall from the core charge" (U3.A212).

> "The $3s^2$ has the lowest ionisation energy as it is further away from the nucleus so there is less effect of the nuclear charge attraction. It is the 2nd electron in the 3s orbital. The $3s^1$ electron requires slightly more energy to remove it as *it has slightly more nuclear charge action[sic] on it once the $3s^2$ electron has been removed.* It is in the same 3s orbital and had spin paired with the $3s^2$ electron. Then there is a large increase due to the changing from 3s orbital to 2p orbital, which means that the 2p orbital electrons are attracted more strongly as they are closer to the nucleus. There is a steady increase as once each previous electron is removed *there is greater attraction by the nuclear charge on the remaining electrons, so the same nuclear charge is pulling on less no. of electrons* so there is a higher energy needed. There isn't a great jump from 2p orbitals to 2s orbitals as they are in the same shell and about the same average distance from the nucleus, but again *there is a greater core charge pulling on less electrons* so higher energy is needed. There is another big jump from 2s electrons to 1s electrons as the 1s electrons are in a shell closer to the nucleus and so are attracted more strongly. More energy is needed to remove the $1s^1$ electron than $1s^2$ electron because *once the [$1s^2$ electron has been removed] there is increased core charge attraction to the $1s^1$ electron*, so has the greatest energy needed."
> (Umar's response to assessment on Periodicity, March 1993 [including edit from crossed-out draft].)

Later in the interview Umar explained that in a sodium atom the "charge on the nucleus to [a specific] electron" would be "plus one", and this was "because ... it's got like eleven protons, eleven pluses in the nucleus and it's got eleven electrons, so it's you know, effectively it's like one plus to each electron, which is one minus" (U3.A262). He thought that if an electron were to be removed the charge on the nucleus acting on one of the remaining electrons would be "stronger, because ... there's the same positive charge is acting on a less number of electrons" (U3.A270). If all but the inner shell electrons were removed the force on one of the remaining electrons "would be much stronger" and this was "because, like, there's an eleven plus force, eleven plus charge, you know, on two electrons, as opposed to eleven, *so, ... effectively five and a half, positive to one minus electron*" (U3.A277). If only one electron remained "they'd be eleven posi¬ eleven plus on the one electron" and so a "much stronger force" (U3.A277).

Umar seemed to still be using this 'sharing' principle in the end-of-first-year examination when he suggested that the molar second ionisation energy of magnesium ... is greater than the molar first ionisation energy ... "because once the 1st electron is removed there is *increased pull from the nucleus on the 2nd electron as it is the only one in that shell*" (A1 examination response, June 1993). When he was interviewed near the end of his course Umar continued to discuss successive ionisation energies in terms of the sharing of the nuclear charge. His discussion of the ionisation of sodium was similar to the explanation he had given in the third interview, eleven months earlier. So in the sodium atom the nuclear charge would be "eleven, pulling on eleven electrons" (U4.A072), and "you need more energy each time you remove an additional electron ... 'cause there's the ***same nuclear charge pulling on less electrons*** so there's a greater elec¬ electrostatic force ... each time" (U4.A072). After the first ionisation, "they'll be ten electrons and eleven-plus nuclear charge so they'll be attracted more, because the ***same positive charge pulling on less electrons***, so, it's ***more on each electron*** [as] the amount of energy [sic] that that nuclear charge used in pulling that outer electron which is one, po¬ one plus, is like ***distributed across the other remaining electrons***, that same energy" (U4.A089).

So according to Umar's understanding, when one electron was removed the nucleus "just attracts [the remaining electrons] more. What it would have used to attract the [eleven] electrons it uses to attract the remaining ten" (U4.A102). If a second electron was removed "then there'll be the same nuclear charge pulling on the remaining nine electrons so it'd be stronger even more" (U4.A110). Each time an electron was removed "there's a stronger nuclear charge on the electrons" (U4.A115), until when only one electron remained "it'd be attracted much more stronger, 'cause there'd be plus-eleven charge pulling on only one electron" (U4.A120).

Appendix 32.

Evidence of octet thinking: atomic ontologies.

§A32.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.1.

§A32.1: An atomic ontology: atoms as the units of matter - the building block metaphor.

In chapter 11 (§11.1) it is suggested that atoms are ascribed a special ontological significance by learners, so that chemical systems tend to be conceptualised in terms of combinations of atoms, although this may not *always* be the most useful and appropriate approach:

§A32.1.1: Kabul.

A particular example may be drawn from Kabul's third interview, when he suggested that two ions would *only* bond together if an electron had been transferred between them. He was asked to consider two hypothetical universes, one created with a sodium ion and a chloride ion, and the other where there had been a sodium atom and a chlorine atom, and an electron has been transferred. Kabul seemed quite happy to enter into such conjectured situations, but in the former case he seemed to assume there must be other species present, "other elements which are possible to gain the electrons from sodium atom" (K3.A116). It seemed that Kabul assumed that if ions were present, electron transfer *must* have taken place,

> I: So are you telling me ... the hypothetical case I set up ... where the universe was created with ions, is that not possible?
> K: I don't think so.
> I: You don't think so?
> K: No.
> K3.A130

Kabul seemed unable to consider the possibility of ultimately starting with ions: in his view whenever there were ions, there must previously have been neutral atoms.

§A32.1.2: Incidental data.

When new A level chemistry students were asked to define the term 'atom' as part of an induction exercise, several suggested that atoms were indivisible. One student defined an atom as, "the smallest part of any substance or element [which] Can not be broken down", and another suggested an atom was a, "particle / element which cannot be broken down" (induction exercise, September 1995).

Another student emphasised that atoms were the smallest components in matter,

> "Everything, every matter is made up of the smallest part called an atom it is the smallest thing in any mater [sic.]"
> (Induction exercise, September 1993.)

§A32.1.3: Incidental data.

Some new A level students' definitions reflected the tension between the atom as being indivisible, and yet a compound entity. So the following suggested definition begs the question of how one knows that the "smallest particle that can be found" has component parts,

> "smallest particle that can be found. Made up of protons, neutrons and electrons"
> (Induction exercise, September 1995.)

This definition implies that the "protons, neutrons and electrons" can not "be found" in isolation. One may similarly consider the implications of the following definition, in terms of the potential status of any sub-atomic structures,

> "an atom is the simplest structure in chemistry. It contains a nucleus with protons and neutrons, and electrons moving around shells"
> (Induction exercise, September 1995.)

§A32.1.4: Incidental data.

Seeing an atom as the basic unit means that molecules are seen as combinations of atoms (rather than as a basic entity, or as a system of atomic nuclei/cores and electrons) and so, according to the students in one class setting out on A level study, a molecule is variously described as in the box:

The molecule defined in terms of atoms:

- formed by two atoms bonding together
- more than one atom, an atom paired with another
- made up of two or more atoms by bonding
- a group of atoms bonded together
- atoms combined
- two or more of the same or different atoms joined together
- two or more atoms chemically combined together
- made up of many different atoms combined to form one
- two atoms joined together chemically

(Induction exercise, September 1995.)

Although there are minor variations in the way in which the idea is expressed, all of these suggested definitions *explain molecules in terms of atoms.*

§A32.1.5: Incidental data.

Ions may be seen as altered atoms, as may be seen in the examples in the box below. Rather than ions being viewed as entities in their own right, they may be seen as atoms (or molecules, which are derived from atoms) that have had electrons added or removed.

The ion defined in terms of atoms:

- either +ve or -ve charge Molecule / Element which has either lost an e- due to some form or manipulation or gained an e-
- a charged particle - when an electron is lost or gained from an Atom / molecule.
- a particle which has an electrical charge, either +ve or -ve. This usually occurs when an atom either gains or loses electrons.
- an atom which has lost or gained electrons, a cation which has a positive charge and an anion (-) charge.
- atoms [which] lose or gain electrons with a positive [sic] or negative charge.
- positively or negatively charged atoms.

(Induction exercise, September 1995.)

§A32.2: The assumption of initial atomicity.

In chapter 11 (§11.1.1) it is suggested that some learners may assume that any chemical system they are asked to consider has evolved from discrete atoms.

§A32.2.1: Tajinder.

For example, in Tajinder's third interview he considered the patterns of melting temperatures across the periodic table. When he was asked about an atom in a piece of carbon he apparently brings to mind an isolated atom (that has "four" outer shell electrons). Only when he is asked to think about a single atom of carbon for comparison, does it occur to Tajinder that carbon does *not* comprise of discrete atoms. Indeed, at first he pauses to think, apparently confused ("carbon atom?") at being asked what seems to him the question he has already answered, and when he is subsequently referred back to the atom in the carbon he is still unsure whether there will be any bonds,

I: Now if you actually had a piece of carbon, > and you >
T < Yeah. <
I: looked at a carbon atom in that piece of carbon, if you could magnify it in some way, how many outer shell electrons would you see?
T: Four
I: Erm, if you took a neon atom, how many outer shell electrons would you see in that?
T: Eight.
I: If you took a carbon atom, how many outer shell electrons would you see in that?
• • • [pause, c.3s]
T: Carbon atom?
• • • • • •
T: Four.
I: If you took a piece of carbon, and you looked at an atom in the piece of carbon, how many outer shell electrons would it have?
T: In a piece of carbon, not in just one atom?
I: Not just one atom.
T: > Oh all right. >
I: < But a < carbon atom within a lump of carbon?
• • •
T: Is it bonded? It's bonded.
I: Well is it bonded?
T: Yeah.
I: So how many electrons would it have in its outer shell?
T: Erm.
• • • • •
T: It'd have eight as well.
T3.A195

It would be usual for learners to consider the structure of diamond and graphite at the secondary level before commencing A level. Tajinder did not recall having done this, but his OCTET RULE EXPLANATORY PRINCIPLE (see chapter 8) might have been expected to lead him to consider stable solid carbon to have a noble gas electronic configuration. Yet shortly after the extract quoted above, Tajinder has reverted to thinking of carbon as consisting of separate atoms,

I: If we take an isolated carbon atom,
T: Yeah
I: how many electrons has it got in the outer shell?
T: Four.
...
I: If you had solid carbon?
T: Four.
• • • • • • [pause, c.6s]
I: What is solid carbon?
T: Graphite or diamond.
I: Graphite or diamond? And do you think they've got four electrons in the outer shell, the atoms in graphite or diamond?
T: Er.
• • • • • • •
T: I'm not sure.
T3.A229

§A32.2.2: Kabul.

A similar example occurred in Kabul's fifth interview when he discussed hybridisation. He talked about diamond as though there were atomic orbitals present, that could be hybridised *when* bonds were to be formed. According to Kabul, the orbitals actually present in carbon, in diamond, were "1s, 2s, ... and 2p" (K5.A458). Kabul suggested there was no hybridisation in the atoms in diamond (K5.A458), "but *when they are to form bonds*, then they undergo ... hybridisation, to get good overlap with one another, and they form bonds" (K5.A463). It would seem that Kabul was thinking of diamond, elemental carbon, as if it consisted of isolated carbon atoms that were yet to hybridise and form bonds.

§A32.2.3: Kabul.

In his final interview Kabul said he thought sodium would react with hydrogen, so he was asked why the hydrogen - which he had classified as stable - should react, and he suggested it was "to become *more* stable" (K6.A283). However his explanation for this was that "each hydrogen *atom* with just one electron, they've still have got, you know, one empty shell [sic], to accommodate another electron you know in order to pair" (K6.A286), which apparently ignored the molecular status of hydrogen. Kabul reiterated that the electron from the sodium would "just pair up ... [with] one of the ... electrons of hydrogen" (K6.A294), before conceding that the hydrogen electrons were already paired up (K6.A299). Kabul did not think the electrons would unpair, (K6.303), and after some thought (a pause of c.27s), made one more attempt to explain why hydrogen should react. However, this explanation was merely a repetition of the argument that had already been discredited, and was aborted,

> "before when they start, they just have one electron in the outer shell, hydrogen atoms, now when they combine they've got two electrons. • • • • • • [pause, c.6s] Hm, dunno."
> K6.A303

§A32.2.4: Incidental data.

Incidental data collected from induction exercises with A level chemistry classes demonstrate that it is not uncommon for learners to make an assumption that reactions occur between elements which are in the form of discrete atoms. The following examples are some suggestions for why there is a reaction between oxygen and hydrogen:

> "Because when Oxygen exists as an atom It has an Incomplete outer shell of electrons. So to [sic] does Hydrogen."
>
> "this reaction occurs because the hydrogen is unstable having just 1 electron in its outermost shell, it joins with oxygen to complete it's outer most shell. 2 hydrogens share 1 electron each from the Oxygen to do this."
>
> "The reaction occurs because hydrogen *needs* 1 electron to complete its shell of electrons and oxygen *needs* 2 electrons in order to complete its outer shell, therefore they *share* the electrons in a covalent bond, so that they both have the required number of electrons in their outer shells."
>
> (Induction exercise, September 1995.)

However, both the reactants, oxygen and hydrogen, are molecular, and do not exist as separate atoms. The third example is presented in anthropomorphic terms. This is a common feature of learners' explanations, which is discussed in the text of the thesis (§11.3). The combustion of carbon may be explained in similar terms, that,

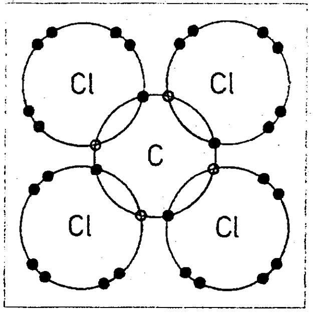
> "carbon which has a valency of 4 *requires 4 more electrons* in order to stablaize [sic] its outer shell. Oxygen which has a valency of 6 and *requires 2 more electrons* in order to become stable. In order for both to become stable one carbon and two oxygen atoms share there [sic] electrons in order to stablalize there [sic] outer shell."
> (Induction exercise, September 1994.)

Again, this response is based on an assumption that, before the reaction, the elements exist as discrete atoms. The same rationale for chemical reactions may be applied in the ionic case, as in the example of sodium reacting with chlorine,

> "Sodiums' [sic] electronic configuration is 2,8,1 and Chlorines' is 2,8,7 so both elements have unstable outer shells. Sodium loses an electron to Chlorine making them both stable and making sodium chloride."
>
> "The reaction takes place due to the transfer of electrons. Ionic bonding takes place and the two elements form the compound NaCl. Sodium needs to lose one electron to be stable and Chlorine needs an electron to be stable therefore Chlorine gains an electron from Na and becomes -ively [sic, negatively] charged whereas Na is +ively [sic, positively] charged. Therefore ionic bonding takes place and NaCl is formed."
>
> (Induction exercise, September 1994.)

§A32.3: Ownership of electrons.

In chapter 11 (§11.1.4) it is suggested that electrons in molecules were commonly seen to *belong to* particular atoms.



focal figure 3

§A32.3.1: Lovesh, Mike, Tajinder, Edward, Carol, Paminder.

So in Lovesh's first interview he explained that, in focal figure 3, the "electrons that are shaded in *belong to* ... chlorine, and the electrons that are, a circle, er *belong to* ... carbon" (L1.A114). When he is probed further Lovesh reveals that his use of 'belong' means "originated from" (L1.A159). Similarly, in Mike's first interview he suggested electrons might be represented differently in diagrams of molecules "to show which electrons *belong to* which, erm, atom", so "the clear circles *belong* to the carbon, the filled-in circles *belong* to the chlorine atoms" (M1.A133). Likewise, in Tajinder's first interview he explained that "this diagram is only trying to represent, which one *belongs* to each, ... this diagram is only trying to tell me, which electron *belongs* to which" (T1.A266). In Edward's first interview, when he was asked about the homolytic bond fission of the carbon-chlorine bond (in tetrachloromethane, focal figure 3) he described how "the chlorine would leave with *its own* valence electron, and the carbon, atom would keep its, *its own* valence electron" (E1.342). (The significance of 'electron history' during bond fission is discussed further in chapter 11, §11.4.1).

In her first interview Carol thought that in focal figure 3 "the [electrons] that aren't coloured in, they *belong* to carbon" (C1.114). Carol thought that there must be some difference between electrons that belonged to different atoms, and suggested that this was "something to do ... with charge" (C1.118). She first suggested "carbon hasn't [charge], I think chlorine has [charge]" (C1.120), but then commented that chlorine electrons "don't necessarily have charge exactly" (C1.122). Another tentative suggestion was that that "carbon [electrons] would be heavier" (C1.136). She said that *had* believed "all ... electrons were the same size" (C1.138), but she now thought “it sounds stupid put like that” (C1.150).

In her first interview Paminder explained that the electrons were drawn differently “just to signify that the dark ones are the chlorine electrons, and these clear ones are the carbon electrons”, and “they’re different because they *belong* to different atoms” (P1.A386). Paminder was asked to explain what she meant by this use of ‘belong’, but at first she could make no sense of the question, and even when it was elaborated, her response instead dealt with *how she knew* which electrons belonged to which atoms. Two interpretations of this exchange which seem feasible are that either,

- Paminder is using the term ‘belong’ as a metaphor (in place of ‘originated on/in’), but this has become a dead metaphor, and is consequently ‘transparent’ to her; or,
- the notion of an electron belonging to an atom is so obvious - one might say that *the atom is the electron’s natural place* - that Paminder is unable to understand the question, as it challenges her very ontology of atoms: perhaps for Paminder it is part of the very essence of an electron to belong in an atom.

The exchange is presented in the following extract:

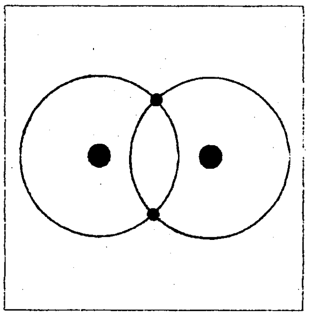
I: So how does an electron belong to an atom?
P: What do you mean?
...
I: You’re saying that this dark one belongs to the chlorine,
P: Mm.
I: and the light one belongs to the carbon. Now I know what I
mean when I say that the tape recorder belongs to me, I’m not
absolutely sure what you mean when you say that the electrons belong
to the atoms. In what way do they belong to them?
P: I think it’s because erm, like, certain, certain erm, tut, erm what
do you call it, elements, they have different number of electrons, okay?
And like chlorine has seven electrons in its outer shell, and carbon has
four electrons in its outer shell, and you can tell from those
characteristics that it’s chlorine [tapping the diagram] and that’s
carbon [ditto]. So if I ignored that,
I: Yeah?
P: and then I counted these seven,
I: Yeah?
P: it can’t be possible for carbon to have seven electrons in an outer
shell if it’s an atom, can it?
I: No, okay.
P: So, and like, similarly, like, if I, if I like erm, just did the clear
ones, carbon has four electrons in its outer shell, and that’s one, two,
three, four. You understand?
I: I understand that, yeah.
P: {laughs}
P1.A386

§A32.3.2: Paminder.

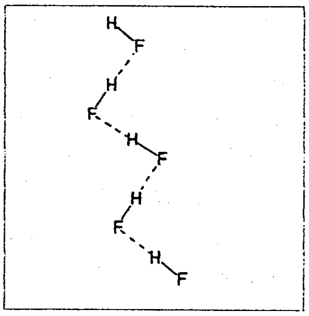
Later in her first interview, after the dialogue quoted above, Paminder suggested that ownership of electrons was a significant factor in the interactions with nuclei, so that in focal figure 3,

> "the protons in the chlorine nucleus, they're attracted to that {poking diagram} particular one, in its own outershell, its *not attracted* to that carbon, carbon's electron"
> P1.A444

Paminder did not think the protons from one atom would attract electrons from another, although she was not completely certain, and accepted that "it could be *possible* like, you know when they're bonded, ... there ***might*** be an attraction", although the attraction to an atom's 'own' electron "would be bigger" (P1.A444). Therefore she thought that if the bond was broken the carbon atom "will keep its electron, and the chlorine will keep <u>its</u> electron, 'cause it's got a stronger attraction with that one" (P1.A444).



focal figure 2



focal figure 22

Later still in the same interview Paminder discussed the hydrogen molecule which was held together by "the covalent bond ... 'cause it's ***sharing*** the electrons" (P1.B013). Her analysis was similar to the tetrachloromethane case, showing that the significant factor was not whether an electron originated in an atom of a particular element, but in a ***particular atom***. Paminder thought that in this molecule "obviously [the nuclei]'d be attracted to ***their own*** [electrons], and ... it could be *possible* that ... they're attracted to the other one's electron as well" (P1.B018). She thought that if she knew which electron came from which atom she would be able to say which electron was attracted most to which atom (P1.B049).

Later in the interview Paminder's own conception of 'belonging' being related to attraction was reflected back at her. She was asked about focal figure 22, which represented a chain of molecules of hydrogen fluoride. Paminder thought there were nine bonds shown in the figure, and that they were ionic bonds, although she was not sure why they were shown differently (P1.B328). More than this, Paminder was quite emphatic that the bonds should be of the same sort. Her argument was that two bonds that were *both* between hydrogen and fluorine should be of the same type, and she demanded an explanation for the two types of line shown in the diagram,

> "Because look, that one's different to that one. Why is that? ... that's an H and that's an H, they're both the same, yeah? H and H. ... And, that's an F, yeah? ... H and H are the same thing. ... So why's that a strong line, and why is that a dotted line? ... Why is that? I, I can't work that out myself, 'cause I think that the bond formed between that and that, will be the same as the bond formed between that and that. {poking diagram} 'Cause they're the same."
> P1.B248

An explanation was suggested to her by making an analogy with her previous comments about the hydrogen molecule. It was put to her that the attraction between one of the nuclei and each of the two electrons in the hydrogen molecule should be the same, as both the electrons were the same. However, Paminder did not agree with the premise of this argument,

> P: I'd disagree, because that electron isn't the same as that one, I don't think.
> I: What's the difference between them?
> P: That one *belongs* to that one, and that one *belongs* to that one.
> I: Right, in that case, number 22, I suggest maybe, on this diagram, that hydrogen belongs to that fluorine,
> P: Yeah.
> I: but that hydrogen belongs to that fluorine. And that's why you > get a >
> P: < Oh yeah, < that's why you get like that. Mm.
> I: So you're happy with that are you?
> P: Yeah.
> P1.B260

My intention in this exchange was to use Paminder's argument about symmetry in the case of H-F to challenge her belief about the two different types of nucleus-electron interactions she perceived in the hydrogen molecule. However this belief was robust, as it was founded on the significance Paminder gave to the electrons *belonging* to a specific atom in the molecule. In borrowing this logic and presenting it in the context of the hydrogen fluoride case I was surprised to find that Paminder did not reject this as nonsensical, or irrelevant, but rather she immediately adopted the reasoning, and accepted the idea she had just found so counter-intuitive, the presence of two bond types in hydrogen fluoride.

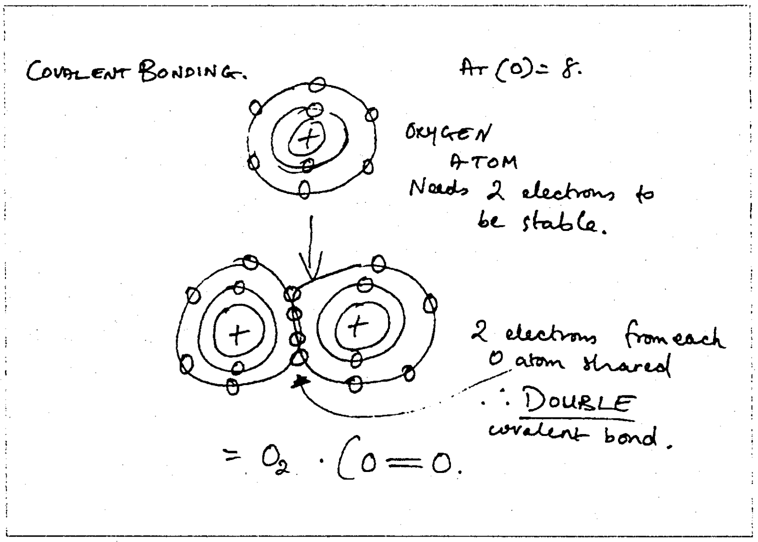
§A32.4: Covalent bonding as sharing of electrons.

In chapter 11 (§11.1.5) it is suggested that learners often described the covalent bond in terms of atoms *sharing* electrons, and seemed to feel that this was a sufficient explanation.

§A32.4.1: Annie, Brian, Carol, Debra, Jagdish, Kabul, Lovesh, Noor, Paminder, Quorat, Tajinder, Umar.

The use of the term 'sharing' was ubiquitous amongst the colearners in this study near the beginning of their A level study. In her first interview Annie described how in the formation of the hydrogen molecule "the two atoms combine and they sort of *share* an electron each" (A1.65), and how the oxygen molecule has a covalent bond (A1.226) where "they're *sharing* more electrons" (A1.230) In Brian's first interview he described covalent bonding as when "the electrons are *shared* to create a full outer shell" (B1.87). In Carol's first interview she gave the definition that "a covalent bond is a *shared* pair of electrons" (C1.86), but she could not explain why that would hold a molecule together as she had "never thought about ... why covalent bonds are what they are" (C1.294). In Debra's first interview she defined the covalent bond as "*sharing* of a pair of electrons" (D1.670), and as when "a pair of electrons are [sic] *shared* by two atoms" (D1.76). She described the hydrogen molecule as "two atoms, joined by a covalent bond, *sharing* a pair of electrons" (D1.64), and defined a double covalent bond as "two pairs of electrons *shared* by each atom" (D1.188).

One of the propositions included in the concept map for 'chemical bonding' Jagdish prepared at the start of her course was that "covalent bonding involves the *sharing* of electrons" (September 1992). In her first interview Jagdish defined a covalent bond as "where electrons are *shared* between two atoms, or more" (J1.A119) and described how a single covalent bond was where "one pair of electrons are *shared*" (J1.A088) and a double bond, as where "two pairs of electrons are *shared*" (J1.A124). During the first term of her course (4.11.92) Jagdish was asked to list, and then try to draw, the different types of chemical bond she knew about. On her diagram for covalent bonding (reproduced, reduced, below) Jagdish shows the covalent bond in oxygen as "2 electrons from each O atom *shared*".



Jagdish's diagram for covalent bonding, November 1992

In a concept map drawn as an introductory exercise at the start of the course, Kabul described the formation of covalent bonding as "*sharing* of electrons" (concept map for 'Chemical Bonding', September 1992). In his first interview Kabul explained that "covalent bonding" means "that they are *sharing* the electrons" (K1.A089) and described a covalent bond as "a type of bond where atoms *share* electrons" (K1.A108), and as "*sharing* of electrons between two atoms" (K1.A395). In Lovesh's first interview he defined the covalent bond as a "bond where electrons are *shared* between atoms" (L1.A075). In Noor's first interview she defined the covalent bond as "when two or more atoms *share* electrons ... in the outermost shell" (N1.A095). In a concept map prepared as an introductory exercise at the start of her course Paminder wrote that "covalent bonding is about *sharing* electrons" (concept map on chemical bonding, September, 1992). In Quorat's first interview she described "a covalent bond, formed between two hydrogen atoms, that are *sharing* their electrons" (Q1.A086). As an introductory exercise in A level chemistry Tajinder prepared a concept map on chemical bonding, including the proposition "in covalent bonding, electrons are *shared*." (September 1992). In his first interview he defined a covalent bond as "where electrons are *shared*, by each of the shells", so in a hydrogen molecule one hydrogen atom "*shares* the other hydrogen's electron" (T1.A111). In his first interview Umar defined the covalent bond as "when they *share* electrons" (U1.A069).

§A32.4.2: Incidental data.

The use of the term 'sharing' was also found in some of the incidental data collected during the research. So covalent bonding is "the *sharing* of electrons in order for atoms to become stable" (induction exercise, September 1995), or "the *sharing* of electrons on the outer shell between two or more atoms" (induction exercise, September 1991).

§A32.4.3: Carol, Debra, Edward, Jagdish, Kabul, Lovesh, Noor, Paminder, Tajinder, Umar.

Most of the colearners continued to talk of 'sharing' even when they had been taught about bonding at A level. In Carol's final interview she still used the term 'sharing' to describe the bond although she related this to the more sophisticated idea of electron density,

> "covalent bond, so, well *shared* pair of electrons means electron density *shared* between the two atoms, so it's got to be symmetrical, ... got to be *shared* equally, I suppose."
> C3.829-31

(Carol's argument here is valid provided she only defines perfectly covalent bonds as a "shared pair of electrons". It is shown in the thesis (§11.6.2) that many colearners tend to dichotomise polar bonds as either covalent or ionic, in which case many bonds classed as covalent would *not* have symmetrical electron density distributions.)

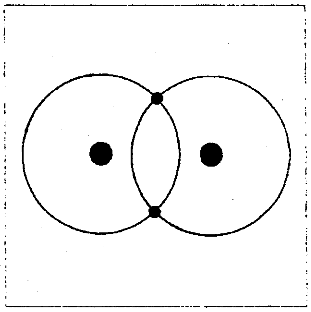
In her second interview, at the start of her second year of A level work, Debra defined the covalent bond as "where a pair of electrons is *shared* between two atoms, more or less equally" (D2.109). In Edward's first interview (which in his case was near the end of his first year), he described how the atoms in a hydrogen molecule were "*sharing*, ... their individual electrons" (E1.165), and how "an oxygen molecule [is] covalently bonded, and they're each *sharing* two electrons" (E1.433).

In her third interview, near the end of her first year, Jagdish identified "covalent" bonding (J3.A527) as "you've got two atoms, but they're *sharing* two electrons, they're *sharing* one electron each" (J3.A527). In Lovesh's second interview he defined the covalent bond as "*sharing* of two electrons" (L2.A289), and in the third interview, at the end of one year of A level work, as "the *sharing* of electrons between two atoms, or more" (L3.A034). At this time Lovesh explained the dative bond as when "you *share* electron pairs, instead of just a single electron", which is possible as "some atoms have lone pair of electrons which they can *share* with other atoms" (L3.A039). In a concept map, prepared as a revision exercise at the end of the first year of his A level course, Lovesh wrote that "covalent bonding involves the *sharing* of electrons where each atom contributes one electron to the bond" (concept map on chemical bonding, June 1993). In Noor's third interview, at the end of a year of A level work, she explained that one type of bond was "covalent which is *sharing* of electrons" (N3.A054).

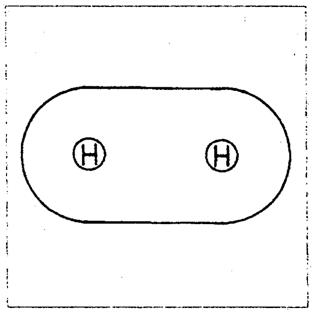
In his third interview Tajinder referred to a covalent bond as "where two atoms *share* electrons to gain a full outer shell" (T3.B332), and in his fourth interview Tajinder suggested that in diamond the bonds were "just a place where you're likely to find the electrons which are being *shared*" (T4.A406), and "they'll *share* the electron. So that is a bond, ... one pair of electrons is a bond" (T4.A406). At the end of one year of A level study Umar still described the covalent bond as a "bond which occurs when 2 atoms *share* a pair of electrons" (concept map on Chemical Bonding, June 1993), and "one in which two atoms join together by the *sharing* of electrons" (end-of-first-year examination response, June 1993). In his second year, in conversation with colearner Lovesh, Umar suggested that a covalent bond was the "*sharing* of electrons between two different atoms" (LU1.A307).

At the end of Paminder's first year of study, in a concept map drawn as a revision exercise, she wrote that "covalent bonding is the *sharing* of electrons between 2 or more atoms - electrons are not completely lost or gained by atoms" (concept map on chemical bonding, June 1993), and in her end of year examination Paminder wrote that "a covalent bond is a bond in which electrons from 2 atoms are *shared* between the atoms (No actual electron transfer is involved)" (end-of-first-year examination, June 1993). In both of these quotations Paminder contrasts covalent bonding with ionic bonding which, as is discussed in chapter 11 (§11.2.2), is often characterised by learners as electron transfer.

In Kabul's second interview near the end of his second term, he referred to how a carbon atom and a hydrogen atom in methane "*share* the electrons" (K2.A124), and he defined a covalent bond as "where electrons are *shared*" (K2.B017). In the fourth interview, at the end of the first year of the course, Kabul still thought that "covalent bonding ... occurs when there is a *sharing* of electrons" (K4.A043). At this point Kabul also knew of "dative bonding [which] occurs when - the *sharing* pair of electrons originate just from one atom" (K4.A049).



focal figure 2



focal figure 7

He described the bonding in focal figure 2 (representing a hydrogen molecule) as "covalent bonding ... because the ... atoms seem to *share* electrons" (K4.A224). Later in the interview Kabul was shown focal figure 7, which he recognised as showing "covalent bonding" (K4.B025). Comparing figure 7 with focal figure 2 Kabul suggested that "number 2 is more simplified" as it "just gives the idea, you know, a covalent bond is formed due to the *sharing* of electrons" (K4.B036).

At the end of the first year of his course Kabul prepared a concept map as a revision exercise, and he described 'covalent bonding' as "formed due to *sharing* of electrons" (concept map on 'Chemical Bonding', June 1993.) Near the end of the first term of his second year Kabul was recorded discussing past examination questions with Tajinder. Again he explained the covalent bond as "just due to the *sharing* of electrons" (KT1.A047). During his final interview Kabul still defined a covalent bond as,

> "a bond formed when two atoms *share* electrons, so, that's what they're doing over here, you know, they overlap and they *share* electrons."
> K6.A173

§A32.4.4: Paminder.

In at least some cases, *sharing* is seen to be an explanation of the bond in itself. This seemed to be the case in Paminder's first interview,

> I: Could you explain to me what holds the two atoms together?
> P: The covalent bond.
> I: Right, so how does that hold the two atoms together?
> P: 'cause it's *sharing* the electrons.
> P1.B013

Earlier she had suggested that the act of sharing was "like a force". She explained that in the hydrogen molecule the atoms remain in place, "because they're *sharing* it, it's kinda like, erm a link, yeah like a stable link that, you know, this one is *sharing* electron with that one, and that one is *sharing*, it's like a force that's holding them together" (P1.A165).

§A32.4.5: Umar

For Umar, as with Paminder, the act of 'sharing' electrons had some particular significance, and was sufficient to explain the bond. In his first interview Umar defined the covalent bond as "when they *share* electrons" (U1.A069), and explained how the bond worked, but not in terms of forces, rather in terms of the process of sharing making them one entity,

> "they're joined together, 'cause first of all they just had two atoms with one electron each, and now they're *sharing* two electrons between them. So it's quite strong ... [because] when they *share* them they're like combined into like one sort of whole thing, instead of two separate atoms."
> U1.A080

Umar reiterated this notion later in the interview,

I: Now, what holds the molecule together in number 2?
U: The two electrons, > • *shared.* >
I: < And how does that hold them < together?
U: 'cause they're *sharing* the same • shell and electron.
I: And why does that hold them together?
U: Makes them more, together like, makes them more like joined together like one.

U1.B446

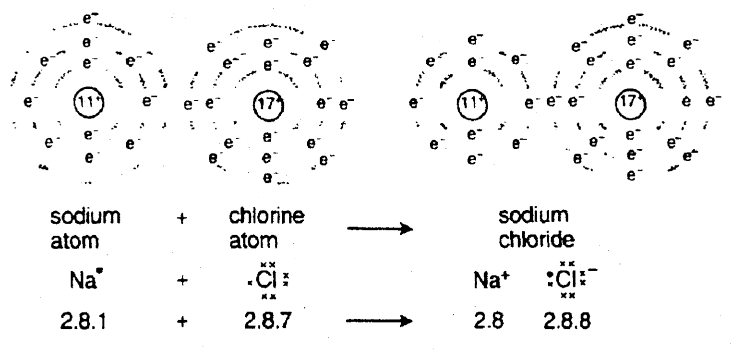
§A32.5: Textbooks suggesting that common materials are formed from atomised matter.

Chemical reactions of importance in the real world consist of processes involving relatively stable materials. This is even true for reactions such as binary syntheses that have little relevance in industry, the environment or biology, but which are considered useful as illustrations in the school or college laboratory.

If sodium chloride is required it will be found in natural deposits. If we require a laboratory preparation we would probably chose a neutralisation process. However if we wished to demonstrate binary synthesis of sodium chloride our reagents would be *metallic* sodium and *molecular* chlorine as these are the elemental forms. Yet in an elementary text this reaction is explained:

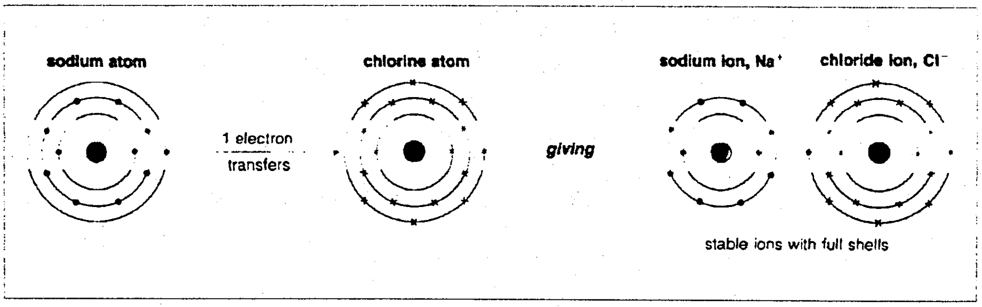
> "The outer electron in the sodium atom is readily given to any other atom that *needs* it. ... Chlorine has seven electrons in its outer shell and during the reaction uses the electron from sodium to give it a full outer shell of electrons."
> Bethell et al., 1991, p.54.

A figure accompanying this text shows *single atoms* of sodium and chlorine, becoming an ion pair, labelled "transfer of electrons during the *reaction between sodium and chlorine*":



The transfer of electrons during the reaction between sodium and chlorine

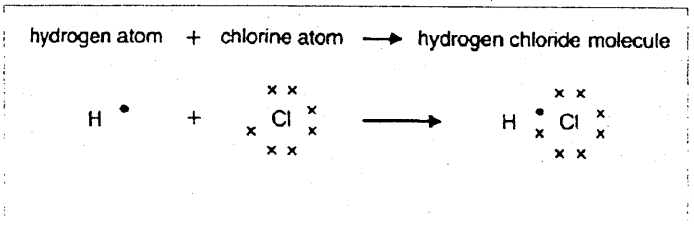
One might wonder whether Bethell et al. are ignorant of the elemental forms of sodium and chlorine. But if they were, then the octet rule that they invoke with such abandon should have alerted them to the instability of atomic sodium and atomic chlorine, and the difficulty in finding sufficient quantities of the atoms for their reaction. However this is not an isolated case, as Gallagher & Ingram also discuss how "...a sodium atom can lose one electron, and a chlorine atom can gain one, to obtain full outer shells" and accompany this with a figure showing electron transfer between a single sodium atom and single chlorine atom (1989, p.42):



This unhelpful approach is not limited to ionic cases. For example Bethell et al. explain the reaction of hydrogen and chlorine,

> "Hydrogen only has one electron in its outside shell, and needs another to make a stable electron arrangement. Chlorine needs one more electron, and shares one of its outer electrons with hydrogen."
> Bethell et al., 1991, p.55.

The accompanying figure shows isolated hydrogen and chlorine atoms forming a molecule - unlike the process that occurs in the *actual* reaction between hydrogen and chlorine:

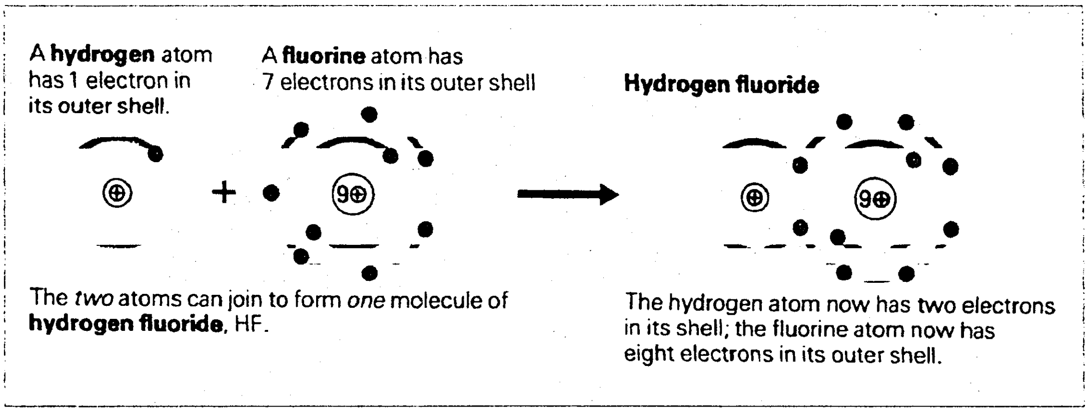


The hydrogen chloride covalent bond

Similarly, Cooper et al. explain covalent bonding thus,

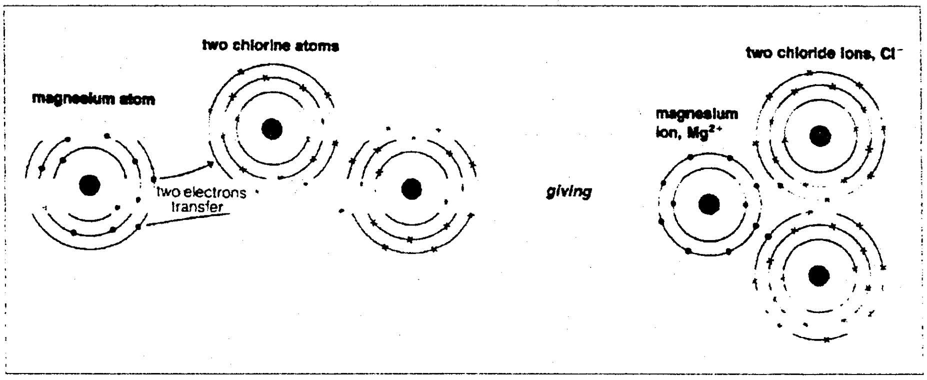
> "Atoms become more stable if they can find a way of filling their outer shells. An atom with an unfilled outer shell of electrons can share electrons with another atom which has an unfilled outer shell - this sharing means that both atoms end up with filled shells. The bond formed by the sharing of outer shell electrons is called a covalent bond."
> Cooper et al., 1992, p.55.

The diagram shows hydrogen fluorine molecules formed from isolated hydrogen and fluorine atoms:



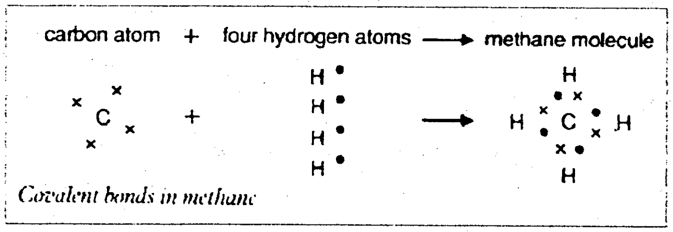
It could be conjectured that there is an element of laziness here. If one wishes to show the formation of hydrogen chloride it might be considered somewhat wasteful to draw whole molecules of hydrogen and chlorine, when only one atom of each is needed to form a molecule of hydrogen chloride.

However, such a conjecture is undermined by the cases where several atoms of a reactant are required, but are *still* shown in diagrams as separate before the formation of the product. For example electron transfer between single magnesium atom and *two discrete chlorine atoms* (Gallagher & Ingram, 1989, p.43):



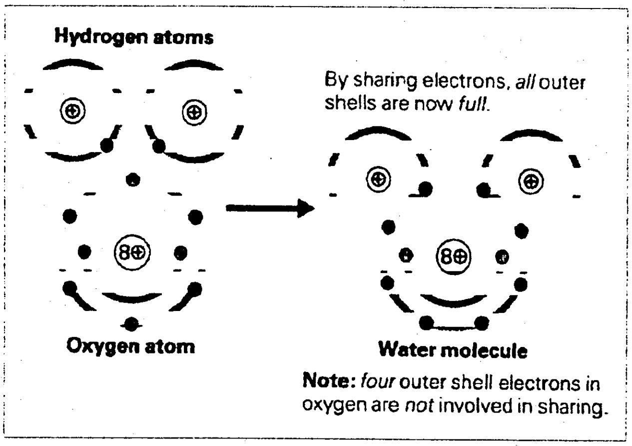
Or the figure accompanying the following text, which shows an isolated carbon atom and *four separate hydrogen atoms*:

> "Carbon has four electrons in its outside shell and needs to share four other electrons before it has a stable electron arrangement. Four atoms of hydrogen will share their electrons with carbon to form a methane molecule."
> Bethell et al. 1991, p.55



Covalent bonds in methane

Another example is a water molecule formed from an isolated oxygen atom and *two separate hydrogen atoms* (Cooper et al., 1992, p.55):



By sharing electrons, *all* outer shells are now *full.*

Note: *four* outer shell electrons in oxygen are *not* involved in sharing.

Appendix 33.

Evidence of octet thinking: the full shells explanatory principle.

§A33.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.2.

§A33.1: The full shells explanatory principle.

In chapter 11 (§11.2) it is suggested that the application of ideas based on the octet rule as the basis for explaining chemical bonding - and related phenomena - is ubiquitous among chemistry learners at this level. All of the colearners in the study seemed to hold in their cognitive structures something akin to the FULL SHELLS EXPLANATORY PRINCIPLE (that atoms form bonds in order to achieve stable electronic configurations - variously referred to as *octets*, *full outer shells* or *noble gas configurations/structures*).

§A33.1.1: The colearners.

Each of the colearners may be shown to be applying a variant of this principle at some point during the interviews:

- Annie described how in the tetrachloromethane molecule "they all share an electron, so the electron circuit is made up by one of each *to give them all full outer shells*" (A2.12).
- Brian described covalent bonding as when "the electrons are shared *to* create a *full outer shell*" (B1.87).
- Carol explained that an atom that had been involved in electron transfer would have "*completed its octet*", and consequently "looks, as though it's pretty stable" (C3.706).
- Debra explained how a carbon atom "*needs* to either gain or lose four electrons *to obtain the configuration of a noble gas*, and be stable" (D1.461).
- Edward explained that in "ionic bonding, and covalent bonding as well" atoms "*like* to achieve a *stable noble gas configuration*" (E1.231).
- Jagdish described covalent bonding as "when you haven't got complete transfer of electrons, and they're *shared* by ... elements, so that the elements can achieve their *stable configuration*" (J3.A061).
- Kabul explained how "in order to attain a stable state you must have *eight electrons*" (K4.B414).
- Lovesh defined ionic bonding as "where you, donate, or gain electrons, *to form a completed outer shell*" (L1.A309).
- Mike explained that between atoms "there would be an attraction in as much that they're balancing out their outer shields [sic] of electrons *so they have eight*" (M1.A448).
- Noor reported that chemical bonding "involves obtaining *a full outer shell*" (N3.A025), and explained how "in all cases what an atom is trying to do is to become stable, and so obtain a *full outer shell*" (N3.A150).
- Paminder described how "in the outer shell, [atoms] need *eight electrons*, ... and to become stable it needs eight, so ... it combines covalently ... so they've both got *full outer shells*" (P1.A136).
- Quorat explained that "the *outer shell of an atom has to be full*, for the atom to be stable" (Q1.A105).
- Rhea described how in ionic bonding "one of them could donate it's electron from its outer shell to *complete the outer shell* for the other one" (R1.A389).
- Tajinder referred to how "all elements try to gain *noble gas configurations* to become stable" (T4.A062).
- Umar explained how in bond formation "each [atom] joins on like to fill in the outer shell it gets an electron each, *to have a full outer shell*" (U3.A323).

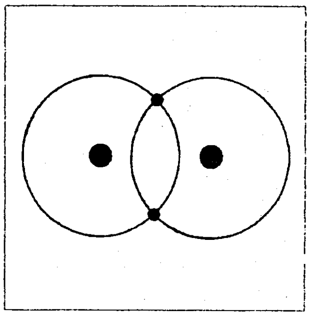
§A33.1.2: Incidental data.

Incidental data provides some evidence that other chemistry learners also apply this principle. Examples of statements collected from students' work included: "atoms are trying to obtain a full outer shell to become STABLE" (from a concept map drawn as an induction exercise, September 1991), and "bonding ... is done in order to try *to achieve a stable structure i.e. 8 electrons in the outer shell* of the atom" (from an induction exercise, September 1995).

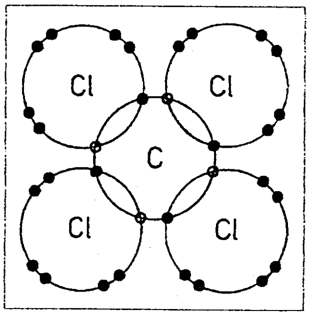
§A33.2: Explaining the covalent bond.

In chapter 11 (§11.2.1) it is suggested that in terms of the FULL SHELLS EXPLANATORY PRINCIPLE, a covalent bond enables atoms to obtain stable electronic structures by sharing electrons, which are then 'counted' towards both of the sharing atoms.

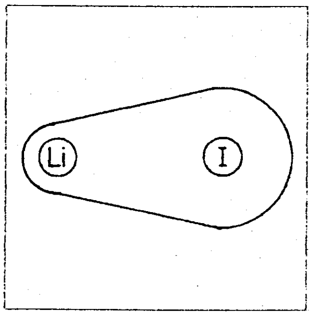
§A33.2.1: Annie, Brian, Debra, Edward, Jagdish, Lovesh, Noor, Paminder, Tajinder, Umar.



focal figure 2



focal figure 4



focal figure 8

Annie for example describes how the two atoms in the hydrogen molecule (focal figure 2) "joined because they only have one electron in their first shell so they combine *to form a stable first shell*" (A1.59); how in the tetrachloromethane molecule (focal figure 3) "they all share an electron, so the electron circuit is made up by one of each *to give them all full outer shells*" (A2.12); and how in focal figure 8 "lithium combines with the iodine, *to make a stable outer shell* between the two, by sharing electrons..." (A1.321). (It is of interest that, despite the shape of the electron cloud represented, the bond between lithium and iodine is considered as covalent, not polar, c.f. §11.6.2).

Brian described covalent bonding as when "the electrons are shared *to* create a *full outer shell*" (B1.87). In Debra's second interview she suggested that the covalent bond in focal figure 3 held the atoms together "because they, they gain *the full shell* then, so they're stable molecules, so it's sort of desirable to be like that" (D2.111). When Edward was explaining the hydrogen molecule during his first interview he described how the atoms were "sharing, ... their individual electrons in a molecule, to ... obtain a stable *noble gas configuration*" (E1.165).

In Jagdish's third interview she described covalent bonding as "when you haven't got complete transfer of electrons, and they're shared by ... elements, so that the elements can achieve their *stable configuration*" (J3.A061) which was "where they're at their lowest energy" (J3.A075). Jagdish was asked about focal figure 2, where she identified "covalent" bonding (J3.A527), as,

> "you've got two atoms, but they're sharing two electrons, they're sharing one electron each, to form the stable energy level, n equals 1, ... because to get a first energy level that is stable, you *need two electrons in it*, and now [each atom has] ... got two electrons for itself ... so it's more stable."
> J3.A527

So for Jagdish 'sharing' was a means by which each atom can get a full shell. A question in the end-of-first-year examination asked for a definition of a covalent bond, and Jagdish said this was "where you have the *sharing* of electrons between 2 species so that *they can both achieve a more stable configuration*" (end-of-first-year examination script, June 1993).

Lovesh explained that hydrogen was more stable in the form of molecules because "in the molecule *the outer electron shell is full*, it's got two electrons, but in an atom it's only got one, and that's not very stable" (L4.A172). Similarly, Lovesh considered tetrachloromethane as stable, because "each atom's got *a full outer electron configuration*" (L4.A226).

In Noor's first interview she explained that focal figure 3 represented a compound,

> "which is CCl_4, because you've got, erm, the aim is *trying* to get the carbon erm *outer ring full*, and so you've added chlorine atoms to it, and they're all sharing, well they'll be giving one of their electrons to the carbon, so you've got four of them, and carbon's got four in its outer shell and it need another four to get, a *complete shell*."
> N1.A100

Here Noor makes it clear that the "aim" for compound formation is to get a full outer shell, which would be "eight" electrons (N1.A100). In her end-of-first-year examination Noor defined the covalent bond in terms of the FULL SHELLS EXPLANATORY PRINCIPLE,

> "Covalent bond - sharing of electrons, atoms share electrons with other atoms so to obtain a *full outer shell* - making them more stable"
> (End of year A1 examination, June 1993.)

In conversation with colearner Jagdish, during the second year of her course, Noor explained covalent bonding as "when you have the sharing of electrons between two species, in order *to gain fully full outer shell*" (JN1.A292).

In Paminder's first interview she defined a covalent bond as "when two atoms, or more, share electrons" (P1.A136). In Quorat's first interview she explained how in the hydrogen molecule (focal figure 2) electrons were shared "between the two atoms ... so that their *outer orbitals are full*, and therefore the atoms, themselves, are stable" (Q1.A100). Later she reiterated that there was "a covalent bond" in focal figure 2, which was "where electrons are shared between ... two or more different atoms ... So that they, their *outer shells are full*" (Q1.A222).

In Tajinder's first interview he explained that "the first shell it needs, two electrons to become stable". So a hydrogen atom would need another electron "to become, to form an, *a full outer shell*" (T1.A111). Even at the end of this interview, after spending time discussing the electrostatic interactions in the hydrogen molecule, Tajinder explained the covalent bond as,

> "where er an electron or maybe two, er one electron is shared by each atom. • • As in the hydrogen, to form an outer shell, *a stable outer shell* it needs another hydrogen, and so - as, as they have one each, they all share one, they all share both, so they both think that they have two outer electrons."
> T1.C208

In his third interview Tajinder defined a covalent bond as "where two atoms share electrons to gain a *full outer shell*" (T3.B332).

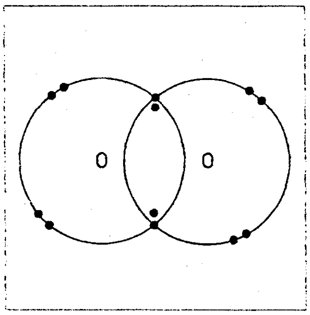
In Umar's second interview for the research he explained how in molecular oxygen the bonding "could be covalent", as "it's got six electrons in its outer shell, and it it *needs to fill them up* again, ... so it bonds with another oxygen, to try *to fill the outer shell*" (U2.A329). In the third interview, at the end of the first year of his course, Umar explained that in focal figure 3 the molecule was drawn as a cross shape (i.e. two dimensionally) to show "how it's bonded to each other 'cause like carbon's got a valency of four in this case, so each one joins on like to fill in the outer shell it gets an electron each, *to have a full outer shell*" (U3.A323). Umar thought it was important for the atoms to "get *noble gas configuration*" (U3.A323). In the end of year examination he wrote,

> "A covalent bond is one in which two atoms join together by the *sharing* of electrons. Each of the atoms *achieves noble gas configuration* in the process of covalent bonding."
> (End-of-first-year examination response, June 1993.)

In his fourth interview, at the end of his course, Umar explained that two hydrogen atoms would tend to form a molecule, as "they're more stable if they form a covalent bond, than forming individual atoms, that is they've got a tendency to become stable by getting *noble gas configuration*" (U4.A203). Umar did not mention the electrostatic field, and his explanation of how the bond might be formed ignored forces, rather "they both have to donate an electron towards the forming [of] a covalent bond, or accept electrons" (U4.A218), that is, "one atom donates its electron, [and] it gains an electron from another one whilst donating one as well, which they share, that's why it's a covalent bond" (U4.A223).

§A33.2.2: Annie, Lovesh, Paminder.

In terms of the FULL SHELLS EXPLANATORY PRINCIPLE, a double bond is simply the sharing of two pairs of electrons. So, in Annie's first interview she explained that in focal figure 4 "they're sharing more electrons, like ... each oxygen is giving two electrons to match up with the other two, so they can each *form a shell of eight*." (A1.230). In Lovesh's third interview, near the end of the first year of his course, he explained that focal figure 4 represents a double bond, with oxygen "sharing two pairs of electrons" (L3.A394) because for oxygen "to get an outer stable electronic configuration, it *needs* to share two pairs" (L3.A399). A stable configuration would be a "*noble gas configuration* ... because it's got *full outer shell* of electrons" (L3.A399).



focal figure 4

In Paminder's first interview she defined a covalent bond as "when, two atoms, or more, share electrons" (P1.A136). She explained why this would happen in the case of oxygen (focal figure 4),

> "They can get a stable outer shell, so that they become more stable, ... in the outer shell, they need *eight electrons*, suppose they've got, say six electrons, ... and to become stable it needs eight, so if you count, if it combines covalently you've got one two three four five six seven eight, one two three four five six seven eight, so they've both got *full outer shells*."
> P1.A136

§A33.2.3: Incidental data.

Comments reflecting the FULL SHELLS EXPLANATORY PRINCIPLE have been presented in induction exercises by students embarking on A level study. The following examples demonstrate how, as with the colearners quoted above, the 'octet' model of covalent bonding is described in various terms:

> "where a substance is held together or bonded ... by the outer electrons of a substance which may be completed by joining to another atoms outer electrons *to attain a noble gas configuration* or a stable state."
> (From an induction exercise, September 1995.)

> "[a covalent bond is] when two different types of atom have spare electrons enough *to fill outer shell.* e.g. Sharing of electrons *to fill outer shell.*"
> (From an induction exercise, September 1995.)

> "Covalent molecules give and take electrons to get to closest *inert gas arrangement of electrons.*"
> (From an induction exercise, September 1991.)

These students use a range of examples to illustrate their understanding of the covalent bond. In the explanations below oxygen, water and methane are used as exemplars:

> "eg. O_2. Each oxygen shares two electrons from each other so that their structures become stable, and they *mimic Neon* which also has *8 electrons in its outer most shell.*"
> (From an induction exercise, September 1995.)

> "Covalent bond - a good example is water as oxygen needs to gain 2 electrons for a *full outer shell* it will join with Hydrogen and share its electrons so Hydrogen shall have *a full outer shell* as well."
> (From an induction exercise, September 1993.)

> "Oxygen and hydrogen both have incomplete shells. So they *complete their shells* by sharing what they have. Hydrogen only has one electron so it needs one more to *complete its inner shell.* Oxygen has 6 electrons in the outer shell so it requires two electrons *to complete its shell.* Two hydrogen atoms complete it to form the water molecule."
> (From an induction exercise, September 1995.)

> "CH_4 methane where they share electrons in order *to complete the outer shell*"
> (From an induction exercise, September 1995.)

> "Carbon has 4 outer electrons in order to *complete it's outer most shell* 4 hydrogens with 1 outer electron join and share each 1 of it's electrons forming a bond, H and C have now *complete outermost shells* + attain *noble gass* [sic] *configurations.*"
> (From an induction exercise, September 1995.)

§A33.2.4: Incidental data.

As has been seen with the colearners interviewed for this research, the FULL SHELLS EXPLANATORY PRINCIPLE is retained and applied by chemistry students after they have been taught the more sophisticated models of the A level curriculum. Again this may be illustrated from incidentally collected data,

> "Covalent bonds occur when two or more elements share electrons to possess a *full atomic shell* in order to become stable."
> (First year assessment, February, 1996.)

> "Covalent bond is the sharing of electrons *to complete full valency shells*."
> (First year assessment, February, 1996.)
>
> "The term co-valent means the sharing of electrons to make *full outer shells* between 2 or more atoms."
> (First year assessment, February, 1996.)
>
> "Covalent bonding is the sharing of electrons by 2 or more atoms to achieve the result of a *full valent shell*."
> (end-of-first-year revision exercise: concept map on chemical bonding, June 1994.)

§A33.2.5: Mike

In chapter 11 (§11.2.1) it is suggested that an interesting variation on the model of covalent bonding discussed here was found in the case of Mike. For most learners applying the FULL SHELLS EXPLANATORY PRINCIPLE, shared electrons are counted fully towards the octets of both sharing atoms. However in his second interview Mike revealed his own interpretation was different, i.e. that a shared electron only counted as half an electron for each atom, so that more electrons would need to be shared to reach the required number. This became clear when Mike was asked to explain the construct of 'having a complete outer shell' that had been elicited in a construct repertory test. In the interview he explained that for him species that had complete outer shells included "any of the noble gases in ... - at the end of the periodic table - group 8" (M2.A335), and "ions of some of the other" elements, such as "chlorine minus, Cl^-" (M2.A340). Mike did not think that hydrogen as it naturally exists, H_2, had a complete outer shell, as each atom "started off with one electron, they're sharing it so they've both now got two electrons, but it's shared between the two of them" (M2.A347). So he thought that "another two" electrons would be needed to give a complete outer shell (M2.A347).

Similarly, in methane, the carbon atom had "got eight electrons orbiting it, on the outer shell, but it's also sharing those atoms with hydrogen, that are surrounding it as well - so, it hasn't really got a full outer shell" (M2.A359), which would require "another four" electrons (M2.A365). Another example was nitrogen which had "five" electrons in its outer shell, but would need "eight" to make a full outer shell (M2.A373). However in ammonia the nitrogen atom would not have a full outer shell "because it would still be sharing the electrons with the hydrogen" so "it'd have eight, but in, *not totally*, it would be in parts, it being shared with the hydrogen", whereas the nitrogen three-minus ion *would* "have a full outer shell" (M2.A379).

§A33.3: Explaining the ionic bond.

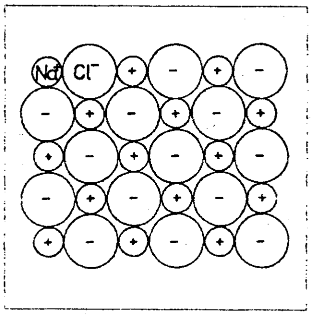
In chapter 11 (§11.2.2) it is suggested that in terms of the FULL SHELLS EXPLANATORY PRINCIPLE, ionic bonding occurs when atoms achieve stable electronic configurations through electron transfer.

§A33.3.1: Annie, Carol, Debra, Jagdish, Kabul, Lovesh, Noor, Quorat, Rhea, Tajinder.

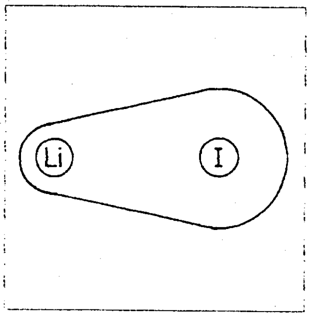
In Annie's final interview, she explained that ionic bonding,

> "involves, one of the atoms donating all of the electrons, to the other one, to the other atom which is sort of deficient in electrons, so making it up to the, number it needs, to like have a *full stable outer shell* which is *what all sort of compounds are aiming for*"
> A4.14

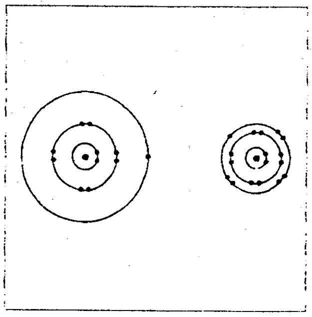
She explained that in the formation of sodium chloride, a sodium atom can be understood to have transferred an electron to a chlorine atom, so "it's gained a stable shell" (A4.46), "because you've removed this electron, you've got ... eight in your next quantum shell down, so that's more stable than having one electron on its own" (A4.76).



focal figure 5



focal figure 8



focal figure 32a

According to Carol, the basis of the attraction in ionic bonding attraction was to be found in the octet rule, or as she explained, "because one's got an extra ... electron, and one ... is electron deficient, so, they want to get like stable, they want to be like stable" (C2.305). In the final interview she suggested that an atom that had been involved in electron transfer would had "*completed its octet*", and "looks as though it's pretty stable" (C3.706).

Debra described the bond between lithium and iodine (focal figure 8) in terms of an electron that "comes from the lithium, to make a *full shell* with the iodine" (D2.294). Note that whereas Annie classed this bond as covalent, Debra here describes it as ionic (D2.296).

Jagdish explained how,

> "most metals are electropositive, ... and they form cations to become ... compounds at a lower energy level, ... So ... they have a tendency to, *give* electrons so they formed positive ions. ... It depends on the valence electrons, ... because [chlorine] has a - tendency to form anions, it's gonna *want*, it's gonna *take* electrons in to form its *full outer shell* ... So I think it depends on some of that. Because it has a tendency to."
> (J3.A152)

Jagdish said that chlorine could not form a bond with sodium by *chlorine* losing one electron, and *sodium* gaining one electron as chlorine "wouldn't have a *stable configuration*" (J3.A214). She explained how a sodium atom could "form a more *stable configuration* by giving one of the electrons to the chlorine and forming a bond, and so it would be at lower energy level" (J3.A376).

Kabul explained how sodium reacted with chlorine by electron transfer to "form a stable compound" (K2.A356),

> "because [the] sodium atom has ... reached its stable ... It has got *eight electrons* in its outermost shell, it does not need any more, or less. And the chlorine also has got *eight electrons*, so ... both of them are stable, they don't need any more, electrons, for reacting."
> K2.A359

This made the material stable as "they've got *full outermost shells*" (K2.A359).

In Lovesh's first interview he recognised ionic bonding in focal figure 5, which he defines as "where you, donate, or gain electrons, *to form a completed outer shell*" (L1.A309). Indeed earlier in this interview it had been established that Lovesh defined ions in a way that *only* included species with full outer shells.

> I: What's an ion?
> L: It's a, it's a charged, atom.
> I: How do you get a charged atoms?
> L: By er adding or losing electrons, gaining or losing (them?)
> I: Ah, so if that atom gains an electron it becomes an ion?
> L: Yeah.
> I: And if it loses an electron, that becomes an ion?
> L: If it, if it gains an electron, and has a *stable out* erm *outside shell*, then it becomes an ion.
> I: And if loses electrons?
> L: Yeah, gains. If it loses an electron, and therefore has a er *completed outer shell*, then it's an ion.
> L1.A235

In a concept map Noor prepared as a revision exercise at the end of the first year of her course, she suggested that "the idea [of ionic bonding] is to attain full outer shells (noble gas config.)"

Quorat discussed focal figure 32a, which showed two atoms, one with "one electron in the outer shell" and the other with "seven in the outer shell" (Q1.B364). She thought these would interact,

> "because this one could donate it's electron to that one, so that would have eight electrons in its outer shell, and so it would be full, and that one would, it had, that, that shell, well we could, we can imagine that it disappears, so it would have an out¬ outer shell that would be full."
> Q1.B369

This would form "an ionic bond" (Q1.B369), and Quorat was clear about why she thought this happened,

I:	Why do they form a bond? ... Why does the electron get transferred?
Q:	Because they want a *full outer shell.*
I:	Why do they 'want a full outer shell'?
Q:	To be stable.
I:	Why does that make them stable?
	• [pause, c.1s]
Q:	Erm. Because the *outer shells are full.*
I:	And that makes them stable?
Q:	Yeah.
Q1.B376	

For Quorat then the 'full outer shell' seemed to provide a sufficient explanation.

When Rhea discussed focal figure 32, part a, she suggested that "one of them could donate it's electron from its outer shell to complete the outer shell for the other one" (R1.A389), and "the one which has got an electron on its own, would donate to the one which has got seven ... [so that] they would both have *full shell outer shells*" (R1.A396).

Tajinder thought an isolated sodium atom was "not stable". To become stable "it would lose an electron" and "that would make it stable" (T1.A135),

> "it would lose the electron then it would ... have a *full outer shell*, a *full outer shell*, because it would have lost that electron to another atom, which would be ... 2.8.7. So that 2.8.7. would need another electron to have a full outer shell, so that chlorine ... I think it is, ... so this electron from the outer shell would go to another one, so then this one would become stable, and also the other one which it goes to would become stable because that would also have *a full outer shell*"
> T1.A135

Tajinder later described ionic bonding in sodium chloride as "where the sodium atom loses the electron to the chlorine atom, then they, they have stable outer shells" (T1.A446). Later when considering focal figure 32 he described how "the metallic atom has one outer electron, only one, and the non-metallic has seven and it needs eight to become stable" (T1.C065).

In his third interview Tajinder continued to explain the ionic bond in similar terms,

> "When two elements form ionic bonds, ... like sodium, and chlorine .... sodium, sort of, to gain a ***full outer shell*** wants to lose an electron, and chlorine wants to gain an electron to become a ***full outer shell.*** So that way it's like, they can form, they can both be stable, together, sodium and chlorine"
> T3.A307

Later in his course, Tajinder continued to describe the ionic bond in these terms, although he acknowledged this was a simplistic approach,

> "Ionic bonding is, ***in simplistic terms*** when you have two atoms, they come come together and ... say sodium and chlorine, and chlorine has got seven outer electrons and needs another electron to have ***a noble gas configuration,*** and sodium has one outer electron and it needs to lose that electron to also gain ***a noble gas configuration,*** and as erm sodium gives it to chlorine, they erm that's ionic bonding ***in simplistic terms.***
> T8.A067

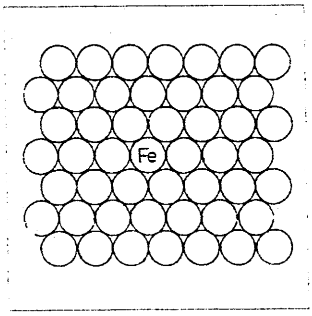
§A33.4: Explaining the metallic bond.

In chapter 11 (§11.2.3) it is suggested that the metallic bond cannot readily be explained in terms of the FULL SHELLS EXPLANATORY PRINCIPLE but that some colearners in the study *were* able to construe the metallic bond in terms consistent with the FULL SHELLS EXPLANATORY PRINCIPLE.

§A33.4.1: Annie, Mike, Tajinder, Umar.

In her final interview Annie explained that although,

> "metals haven't got full, ***full outer shells,*** then by electrons moving around, they're, they're getting, ***a full outer shell,*** but then they're sort of losing it, but then like the next one along will be receiving ***a full outer shell***"
> A4.84



focal figure 6

In Mike's first interview he considered focal figure 6. Mike referred to 'balancing out' of an atom's 'outer shield' (a term he used for shell). So between the iron atoms "there would be an attraction in as much that they're balancing out their outer shields of electrons so they have *eight*" (M1.A448). At this stage he explained how this was achieved in terms of electrons being shared,

> "if an atom has, say like, six electrons in outer shield, it would need two more electrons from another substance to balance, ***make it up to an eight.*** So another atom's got to share two extra electrons, to build up the outer shield."
> M1.A448

From focal figure 6 Mike deduced that iron needed six electrons to fill up its outer shell (M1.A457).

Tajinder also conceptualised the metallic bond in terms of the FULL SHELLS EXPLANATORY PRINCIPLE,

> "because in lithium atom, yeah, there's one outer electron, so it's not stable it hasn't got, it can gain a *noble gas configuration* if it loses an electron, and so it's quite high energy, so it wants to become lower energy, in this one it's like doing that by constantly losing an electron, well not losing but giving it away, passing it around, sort of thing"
> T3.B131

Umar was also able to apply the FULL SHELLS EXPLANATORY PRINCIPLE to metallic structures. He thought that iron atoms would spontaneously form a metallic lattice, but again this was not due to electrostatic forces, but rather because,

> "in the lattice each ion is erm, is a positive ion so again achieves ... loses an electron to form a positive ion, so *to get a noble gas configuration.*"
> U4.A538

This utterance came in his final interview, near the end of his course: that is after Umar had been taught about models of metallic bonding involving electrostatic forces, and the overlap of valence shell atomic orbitals giving rise to an extensive system of molecular orbitals. Similarly, the following definition is from a revision exercise undertaken by a student at the end of the first year of the A level course,

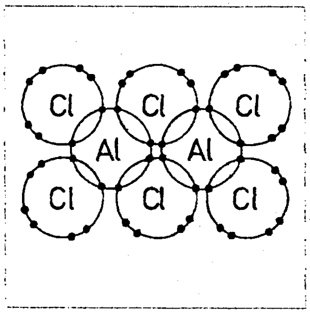
> "metallic - formed by the one, two or three valent shell electrons being donated to lattice *so a noble gas configuration is achieved.* The electrons hold the atoms together."
> (From a concept map on Chemical Bonding, June 1994.)

§A33.5: Explaining the dative bond.

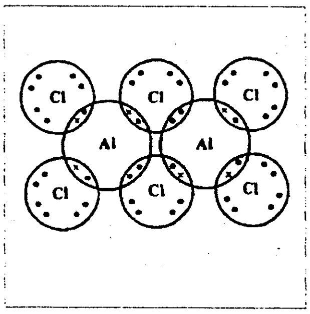
In chapter 11 (§11.2.4) it is suggested that colearners were able to apply the FULL SHELLS EXPLANATORY PRINCIPLE as a rationale for dative bonding.

§A33.5.1: Annie, Kabul, Lovesh, Noor.

Annie explained that in focal figure 15, aluminium has "got the amount that it needs, to stabilise" (A1.608).



focal figure 15



triad element 249

In the fourth interview, Kabul used the notion of octets to explain why dative bonds should form in aluminium chloride,

> "aluminium has a valency of three, it forms three covalent bonds. So in total aluminium has got six electrons .... Three and one from each atom. But in order to go to you know G.C.S.E. format, which says ... in order to attain a stable state you must have *eight electrons*, so one of the chlorine atoms seems to donate two electrons, and form a dative bond."
> K4.B414

Although Kabul labels this argument as the "G.C.S.E. format", the *only* reason he suggests for the dimerisation is "in order to attain a stable state you must have eight electrons", i.e. he does not suggest what a "post-G.C.S.E. format" explanation might be. During the second term of his second year Kabul had undertaken Kelly's construct repertory test. The elicited constructs were followed up in the fifth interview when Kabul discussed *triad element* 249. He explained the molecular association in terms of his octet framework, that,

> "...if you look at the number of electrons, there are six electrons, and you can go back to your G.C.S.E., you know, {laughs} explanations, and say, they have to have *octet*, you know, *eight electrons*, so the other two electrons are just donated by chlorine because you know chlorine atoms have got lone pairs, isn't it {tapping diagram} they can just donate them to aluminium, and, you know, they become linked."
> K5.B188

Again, Kabul was aware he was falling back on his "G.C.S.E" knowledge, but he did not offer an alternative explanation. In his final interview, shortly before his A level examination Kabul reiterated that the dative bond in aluminium chloride formed "to obtain the octet state, because octet state is usually stable" (K6.B128).

Lovesh explained that aluminium chloride formed dimers because "in $AlCl_3$, the aluminium hasn't got an outer, a stable outer electron configuration, [whereas in the dimer] it has ... and so it really *wants* to attract two electrons to become stable" (L4.A514).

Noor also explained dative bonding using the FULL SHELLS EXPLANATORY PRINCIPLE She said that a dative bond forms between molecules of aluminium chloride,

> "Because if you just had a covalent bond between aluminium and chlorine say, say if the valency of aluminium was three, then you'd have three chlorines surrounding it, but to obtain a *full outer shell* it would need two more electrons, and it gets them from the chlorine, 'cause the chlorine overlaps, it gets, it gets them from another chlorine which overlaps with it and shares its electrons with it."
> N3.B322

§A33.6: Rationale for chemical reactions.

In chapter 11 (§11.2.5) it is suggested that the FULL SHELLS EXPLANATORY PRINCIPLE may be used to explain chemical reactions, as well as bonds in themselves.

§A33.6.1: Debra, Lovesh.

In her final interview (after discussing how hydrogen would bond in terms of the lower energy of the molecular orbitals) Debra suggested that the reason helium did not form a diatomic helium molecule molecule was because the atoms have "already got *full shells*" (D3.37). Although she had learnt - and had just been discussing - a model of bonding based on molecular orbitals, she did not apply these ideas to helium, but explained its lack of reactivity in terms of the FULL SHELLS EXPLANATORY PRINCIPLE.

In Lovesh's second interview he explained that some atoms, but not all, are stable,

> "like noble gases, they don't react because they've got of complete outer electron, outer shell, so ... it doesn't need to donate or accept to becomes a complete, orbital."
> L2.A564

§A33.6.2: Kabul, Lovesh.

Near the beginning of Kabul's first interview, he alluded to stable electronic structures when he described focal figure 2 as representing "hydrogen gas, probably" because hydrogen "has got one electron in its outermost shell, and *it cannot exist on its own*, so it will combine with another hydrogen, to form hydrogen molecule" (K1.A077).

In his final interview Kabul started to discuss a reaction in terms of the *electrostatic* interactions between the nucleus of one atom and the electrons of another. However the explanation soon shifted from *electrostatics* to *octets*,

> "two [interacting species] come close to each other, and the nucleus attracts this electron towards itself, and this one is quite happy to give it away, because it comes more stable. So ... [for] example you know, if you say it's an oxygen atom, ... it has got six outer electrons, each oxygen atom, ... so they, each oxygen has needs, you know, about [sic] 2 electrons to become more stable so you know they form the *octet*, and - they accept electrons."
> K6.A243

Kabul thought sodium would react with hydrogen, and when he was asked why the hydrogen should react, he explained that "each hydrogen atom with just one electron, they've still have got, you know, one empty shell, to accommodate another electron you know in order to pair" (K6.A286). Kabul is here making the assumption of initial atomicity (§11.1.1), whereas according to CURRICULUM SCIENCE hydrogen would actually be in the form of diatomic molecules.

In Lovesh's final interview, where he still used the FULL SHELLS EXPLANATORY PRINCIPLE, he was not able to explain why two apparently 'stable' species should react,

I: ... so I've got some [oxygen] and some [hydrogen], do you think that'll be a stable mixture?
• • • [pause, c.3s]
L: Erm,
• • • • • • • • • • •
L: yeah I think it would be, but if, if you had a spark, like a bit of energy then it could be explosive.
I: So, why's that then?
•
I: Why, why do you get an explosion?
• • •
L: Erm.
• • • •
L: I don't know.
L4.A244

§A33.7: Octets, or full shells, or noble gas electronic configurations?

In chapter 11 (§11.2.6) it is suggested that colearners were unclear about what should actually be considered to be a full electron shell.

§A33.7.1: Edward.

Edward explained in his first interview that in "ionic bonding, and covalent bonding as well" atoms "like [sic] to achieve a stable *noble gas configuration*, which are, two in the first shell, eight in the second, and it goes up according to $2n^2$, depending on the shell" (E1.231). This should lead to a prediction of $2(3^2)=18$ electrons in the n=3 shell. However, in the final interview, shortly before his examination (when he should have been aware of the importance of 3d orbitals both in transitions metals, and where elements in the third period 'expand their octet'), Edward stated that the third atomic shell could only contain four orbitals (E2.A125, A167), which would imply a maximum of eight electrons. He later explained that the second shell could contain more electrons than the first "because there's more electrons [which] repel each other, so for a shell to accommodate eight electrons it would need a bigger volume, to compensate for the electron repulsion" (E2.A167). However when it was suggested to Edward that this argument could be extended to the third shell, so it would take more than eight electrons, he disagreed as "no, it's not possible, the maximum you can have is 8 electrons ... because that's, gives it a certain amount of stability, 8" (E2.A183). Edward could not suggest why this should be so, and felt he was in "uncharted territory" (E2.A183).

A34.7.2: Jagdish, Paminder.

Jagdish was also confused over the number of electrons that would give a full shell,

> "doesn't ... an outer shell need, don't certain energy levels have a number of electrons that they *must* have to be stable, like the first energy level has two electrons, needs two electrons to be a stable configuration, and the second one is eight, the third one is eight, then you go back to it's eighteen or something."
> J3.A230

Paminder thought that a full outer shell was not always eight electrons, as "in a few shells you can have eighteen" electrons (P1.A136): so in the first shell there were "two, maximum", and in the second shell "eight", and in the third shell "eight", and in the fourth shell "eight or eighteen" electrons (P1.A152).

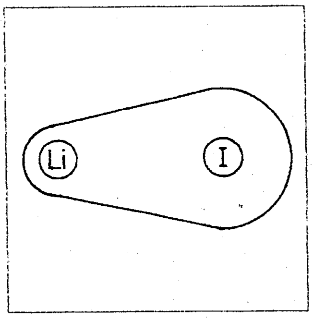
§A33.8: Bond polarity and electronegativity.

In chapter 11 (§11.2.7) it is suggested that some of the colearners would attempt to rationalise polarity in terms of octets.

§A33.8.1:Jagdish, Noor.

In her third interview Jagdish discussed the polarity of a bond as being due to the extent to which the elements involved "pull electrons in a bond" (J3.A136), but this was construed in terms of forming "*its full outer shell*" (J3.A152),

> "I think, does it depend on how erm what it has to do to get to a lower stage, lower level, because like metals, metals, most metals are electropositive, ... and they form cations to become ... compounds at a lower energy level, ... So ... they have a tendency to, *give* electrons so they formed positive ions. ... It depends on the valence electrons, ... because [chlorine] has a - tendency to form anions, it's gonna *want*, it's gonna *take* electrons in to form its *full outer shell* ... So I think it depends on some of that. Because it has a tendency to attract electrons anyway, and electronegativity is the tendency to pull electrons in a bond, I think it is connected."
> (J3.A152)



focal figure 8

Jagdish identified the bonding in focal figure 8 as polar (J3.B332), which she explained using the idea that iodine is more electronegative than lithium. However, when asked to explain why this should be so, she could only suggest that iodine "has seven valence electrons, and it *has to have eight* to be more stable" (J3.B341).

In Noor's third interview she set out to explain electronegativity, but her explanation was in terms of octets and was limited to discriminating metals from non-metals,

> "in all cases what an atom is trying to do is to become stable, and so er obtain a *full outer shell*. In the case of metals it's easier for them to become stable by losing electrons, and, by doing this they become positive, so they're gonna be more electropositive, whereas [non-metals] to become stable erm would acquire those electrons, and hence become more electronegative, 'cause they've gained electrons"
> N3.A150

Similarly, in a concept map prepared as a revision exercise at the end of the first year of her course, Noor wrote,

> "Electronegativity - the more electronegative species are the non-metals as they have the greater tendency to acquire electrons to *complete their outer shells*."
> (concept map on chemical bonding June 1993.)

§A33.8.2: Kabul.

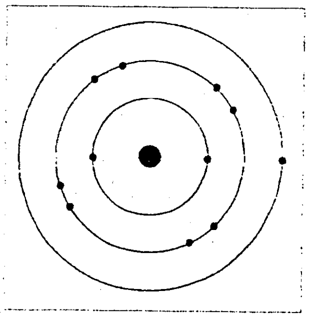
In Kabul's final interview he attempted to explain why chlorine should be more electronegative than carbon in the terms that,"chlorine has got, you know, seven electrons in its outermost shell ... It just needs one electron to become stable, ... whereas carbon needs four electrons to become more stable, so it's less electronegative" (K6.A322). Sodium was more electropositive than iron because "there's just one electron in its outermost shell. So it's easier for sodium to lose just one electron and obtain its octet state" (K6.A426).

§A33.9: Stable electronic structures.

In chapter 11, (§11.2.8) it was suggested that although the FULL SHELLS EXPLANATORY PRINCIPLE is used by colearners in ways that are here considered invalid, it is none-the-less based on an established principle from CURRICULUM SCIENCE, that some electronic structures appear to be associated with particular stability.

§A33.9.1: Lovesh.

In Lovesh's final interview, near the end of the second year of his course he explained how a sodium atom is not stable "because it hasn't got a, a full outer-electron shell, [the] outer electron shell hasn't got eight electrons in" (L4.A067). Indeed Lovesh thought that "it's not possible to have one on its own" (L4.A26).



focal figure 1

§A33.9.2: Quorat, Kabul, Umar.

Quorat explained that she did not think a sodium atom was stable,

> "because the outer electron shell is not full, and therefore that electron has to be lost, in order to make, in order to have a, *outer shell full*. The outer shell of a, of an atom has to be full, for the atom to be stable."
> Q1.A105

During his final interview Kabul suggested that a magnesium atom was "not stable" (K6.A067), "because the two electrons, still there are, you know, empty shells [sic, i.e. orbitals] to accommodate electrons, so it's not stable" (K6.A070).

In Umar's first interview he explained how he thought that although atoms sometimes attracted electrons from other atoms if they were not full, if an atom "was *full of like eight*, then like, I don't think it would attract [an additional electron], because it would be *full* and it wouldn't need another electron, but if it had seven, and another one had one on the outer shell then it would attract, some one, some other electron" (U1.B464). Even when he was asked about the integrity of a molecule, Umar answered in terms of octets, explaining that a chlorine atom would not fall off a molecule of tetrachloromethane as "it's stable, it's valence shell is stable *'cause it's got eight electrons in its outer shell*" (U4.A300).

§A33.10: Ionisation energies.

In chapter 11 (§11.2.9) it is suggested that the FULL SHELLS EXPLANATORY PRINCIPLE criterion of atomic stability may be seen to effect learners' understanding of ionisation energies.

§A33.10.1: Lovesh.

So for example Lovesh had studied patterns in ionisation energies, but in the context of the interview discussion of the stability of the sodium ion (§A33.9.1) he appeared to be operating from his FULL SHELLS EXPLANATORY PRINCIPLE perspective, from which a second ionisation of sodium did not make sense,

> I: Is it possible to remove, say, a second electron, one of these?
> L: After you've removed that?
> I: Yeah.
> L: Erm, I don't think it's possible with sodium.
> I: Not with sodium?
> L: No.
> I: So you couldn't have, say, the second ionisation of sodium?
> L: Not really, no...
> L4.A145

§A33.10.2: Incidental data.

Data collected from students' responses to a past examination question about ionisation energies reflected this sample of dialogue with Lovesh. It would seem that when a question concerns one of the noble gases then the observed stability of the noble gas electronic configurations may be invoked as an explanation, rather than as a phenomena to be explained. The question, used in the end-of-first-year examination given to A level chemistry students in June 1994, asked *why neon had the highest molar first ionisation energy of the elements in period 2*. The most appropriate answer from a curriculum science perspective would focus on the core charge, which increases across the period. However, even when this *is* invoked, the full outer shell status may also be mentioned as another reason. A number of students, however, gave a response that suggested that the high ionisation energy could be explained completely in terms of the FULL SHELLS EXPLANATORY PRINCIPLE. Once again the precise wording varies considerably, with *full shells*, *eight electrons*, *octets* and unspecified *stable configurations* variously used to make the point,

> "Neon has a *stable outer shell* and so to get one electron out of that *full shell* would require alot of energy as it is firmly in place and attracted to the nucleus."
>
> "... Neon is in group 0, and is *stable electron shell*, and lots of energy must be put because of its stability."
>
> "Neon has *full outer shell* so it is difficult to remove an electron from a filled shell.
>
> "Neon has a *full outer shell* (electronic configuration 2/8) therefore its electrons are very stable and so it requires more energy to pull one electron out."
>
> "Neon has *eight* electrons in its shell and therefore contains a *full shell* making it very difficult to remove electrons."
>
> "Neon follows the *Octet Rule* in that it has a Stable base ie it has a *full Valence shell of 8 electrons*. ∴ A lot more energy is required to remove one electron because of this *stable configurations*."
>
> "... it has a *full valent shell of eight electrons* which renders it very stable and unreactive. Due to this a huge amount of energy is required to remove the first electron from it."
>
> "Neon is inert gas *electron shells are full*, electron configuration satisfied."
>
> "[neon] is an inert gas so it is very stable because it has *8 electrons in its outer shell*"
>
> "... it has achieved it's *octet* ie its second shell is *full with eight electrons* and cannot take any more so to remove 1 of these will disrupt the configuration as all charges are balanced out and ∴ it is very difficult."
>
> (End-of-first-year examination, June 1994)

§A33.11: Text book examples of the octet rule expressed as an explanatory principle, rather than a heuristic device.

The way in which some texts discuss the octet rule is of interest. For one thing the term 'octet rule' itself is seldom *explicitly* used. For another, although the idea may be initially presented as an observed *correlation* between certain electronic structures and chemical stability, subsequent text may imply that stability is therefore *explained* by noble gas configurations,

> "The noble gases are unreactive *because* their atoms have full outer shells of electrons."
> Gallagher & Ingram, 1989, p.33.
>
> "The noble gases ... do not usually form compounds,... For this reason, their atoms are described as unreactive or stable. They are stable *because* their outer electron shells are full: A full outer shell ***makes an*** *atom stable*."
> Gallagher & Ingram, 1989, p.40.

Having an *octet* does not intuitively suggest stability, but the catchy phrase "full outer shell" may well do - even though it is technically suspect (see below, §A33.3.3). Once the notion of full shells being stable is established it may be used to explain the 'purpose' of bonds, so that "in covalent bonds, pairs of electrons are shared *so that* the outer shells are full" (Oxford Science Programme, 1993, p.22). Further, as bonds are formed during chemical reactions the 'explanatory principle' may be extended,

- "Only the noble gas atoms have full outer shells. The atoms of all other elements have incomplete outer shells. *That is why they react*: By reacting with each other, atoms can obtain full outer shells and so become stable" (Gallagher & Ingram, 1989, p.40).
- "...atoms *try* to get this stable arrangement of electrons when they take part in chemical reactions" (Holman, 1991, p.222).
- "Chlorine has seven electrons in its outer shell and during the reaction uses the electron from sodium to give it a full outer shell of electrons" (Bethell et al., 1991, p.54.)
- "...a sodium atom can lose one electron, and a chlorine atom can gain one, *to* obtain full outer shells" (Gallagher & Ingram, 1989, p.43).

What is conveniently forgotten when such statements are made is that in chemical reactions bonds are broken as well as made, so that although the octet rule could 'explain' why atomised materials would 'react', it has little relevance to the chemistry that is met in school, industry or everyday life.

§A33.12: Confusion between octets, full shells and noble gas electronic configurations.

The octet rule is really concerned with the stability of noble gas electronic configurations. The term octet means a set of eight electrons, and therefore is technically inappropriate for period 1 (hydrogen and helium). For periods 1 and 2 the noble gas electronic configuration is equivalent to having electrons shells that are all either full or empty, thus the term 'full outer shell'. However for period 3 and beyond noble gas structures do not involve full outer shells. Argon is ten electrons short of a full outer shell, and Xenon is not only 24 electrons short of a full outermost shell, it is also 14 electrons short of a full outermost-but-one shell.

Yet elementary text book authors ignore (or perhaps are ignorant of) these complications, and tell their young readers

- "When atoms of some elements are involved in chemical reactions, they obtain stable electronic structures like those of the noble gases - *all their electron shells are full*" (Cooper et al., 1992, p.33).
- "Atoms become more *stable* if they can find a way of *filling their outer shells*" (Cooper et al., 1992, p.55).
- "The noble gasses are unreactive because their atoms have *full outer shells* of electrons" (Gallagher & Ingram, 1989, p.33).
- "The noble gases ... do not usually form compounds, ... For this reason, their atoms are described as unreactive or stable. They are stable because their *outer electron shells are full*: A *full outer shell* makes an atom stable. ... By reacting with each other, atoms can obtain *full outer shells* and so become stable" (Gallagher & Ingram, 1989, p.40).
- "When two non-metal atoms react together both of them need to gain electrons, to reach *full shells*" (Gallagher & Ingram, 1989, p.46).
- "If atoms acquire a *full outer shell* of electrons they become more stable" (Jarvis et al., 1993, p. 15).

It might be argued that it is acceptable to introduce the idea of full outer shells as a general notion, provided that when period 3 elements are considered the idea is developed. One book considered did attempt to do this (Oxford Science Programme, 1993, see below), but others preferred to give readers factually incorrect information:

- "When atoms of elements in Groups 1 to 8 are involved in chemical reactions they try to obtain noble gas electronic structures. They try to *fill their shells* - the first shell can hold 2 electrons and the *other shells 8 electron each*" (Cooper et al., 1992, p.37).
- helium, neon, *argon* "... all have filled outer shells of electrons. ...Scientists believe

that their stability comes from having a *filled outer shell*" (Holman, 1991, p.222).

- "Chlorine has seven electrons in its outer shell and during the reaction uses the electron from sodium to give it a *full outer shell* of electrons" (Bethell et al., 1991, p.54).
- "A chlorine atom needs a share in one more electron, to obtain a *full shell*" (Gallagher & Ingram, 1989, p.46).
- "Each shell has a limit to the number of electrons it can hold ... Two electrons fill the first shell. ... Eight electrons will fill the second shell. ... *Eight electrons will also fill the third shell*" (Cooper et al., 1992, p.54).
- "Each shell can hold only a limited number of electrons: the first shell can hold up to 2 electrons, the second shell can hold up to 8, the *third shell can also hold up to 8*" (Gallagher & Ingram, 1989, p.26).
- "The third shell can hold *up to 8* electrons" (Jarvis et al., 1993, p. 47.)
- "the first shell can hold up to 2 electrons, the second up to 8, and the third *up to 8*" (Pople, 1994, p.47).

One book - part of the Oxford Science Programme - did attempt to provide an accurate account. One student is shown to say that "in covalent bonds, pairs of electrons are shared so that the outer shells are full. The first shell can hold 2 electrons, the second 8 and the third 8 as well." Another replies that he thought "18 electrons were allowed in the third shell." The first student agrees, explaining "but 10 of those electrons are treated separately." She reports that the teacher had told her "not to worry about those yet" (Oxford Science Programme, 1993, p.22). On the previous page the text had reported that,

> "The third electron shell can hold 18 electrons. However, in diagrams, it is usually shown with only 8 electron spaces. This is because it *behaves like a full shell* when there are only 8 electrons in it."
> Oxford Science Programme, 1993, p.21.

Whilst the attempt at accuracy is admirable, there is a certain amount of tautology involved, i.e. the argument seems to be that:

1. Atoms are stable if they have noble gas configurations.
2. This is because they have full shells of electrons,
3. and a full shell is stable.
4. Actually most of the noble gases do not have full outer shells,
5. but they behave as if they do,
6. because they are stable,

and

1. atoms are stable if they have noble gas configurations.

...

Appendix 34.

Evidence of octet thinking: anthropomorphic language.

§A34.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it emerged (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.3.

§A34.1: The use of anthropomorphic language to discuss atomic phenomena.

In chapter 11 (§11.3) it is suggested that colearners tended to give explanations based on the FULL SHELLS EXPLANATORY PRINCIPLE in language that was anthropomorphic, that is, atoms were spoken of *as if* they were sentient actors that had perceptions and desires, and were able to act accordingly.

§A34.1.1: Annie, Kabul, Paminder, Debra, Edward, Jagdish, Tajinder, Umar.

One way in which the FULL SHELLS EXPLANATORY PRINCIPLE was applied by the colearners was by referring to how atoms *needed* to acquire (or lose) electrons to become stable. For example, Annie explained the formation of the covalent bond in hydrogen in these terms, that "the two atoms combine and they sort of *share* an electron each, so they sort of combine, so they've got two electrons between them, and they've each contributed one to the shell ... because they're sort of like unstable because ... hydrogen's only got like one electron anyway, so it *needs* to combine so it can be more stable" (A1.65, 77).

Kabul explained that once an atom had formed the right number of bonds it would not *need* any more electrons,

> "Oxygen's got six electrons. It uses two of its electrons to bond covalently with ... two other electrons from the [other] oxygen atom, and if you count the total number outside, they are, you know, eight, they add up to eight, so it doesn't *need* any more.
> K5.B460

Paminder explained that the right number of bonds was different for different atoms,

> "hydrogen only *needs* to form a single bond 'cause it only has to *share* its outer electrons, where, 'cause it's got one electron in its outer shell, it just *needs* another one, to have two to form a noble gas configuration, so if it gains one from ... another hydrogen they'll both have two electrons in their outer shell. While oxygen has got six, so it *needs* two more, that's why it has to *share* with two pairs of electrons."
> P3.A589

There were other examples of colearners references to atoms' needs:-

- iodine "only *needs* like one electron" (Annie, A2.119).
- the valency of carbon was four which "means that it *needs* to either gain or lose four electrons to obtain the configuration of a noble gas, and be stable" (Debra, D1.461).
- in noble gas configurations "each orbital in each shell is filled, and it doesn't *need* to acquire electrons, or, lose electrons, to fill all its shells" (Edward, E1.233).
- the oxygen atom "*needs* 2 electrons to be stable" (Jagdish, legend to diagram of covalent bonding, November 1992).
- in sodium chloride "the sodium atom ... does not *need* any more, or less [electrons] ... both [sodium and chlorine] are stable, they don't *need* any more, electrons, for reacting" (Kabul, K2.A359).
- "an oxygen atom, ... has got six outer electrons ... so they, each oxygen, has *needs*, ... [for] 2 electrons to become more stable so you know they form the octet" (Kabul, K6.A243).
- "chlorine has got, you know, seven electrons in its outermost shell, so it ... just *needs* one electron to become stable, and - so - it's more electronegative than carbon, whereas carbon *needs* four electrons to become more stable, so it's less electronegative" (Kabul, K6.A322).
- a sodium atom was not a stable species because "it *needs* to, erm, lose that outer electron to become, to have a stable electronic configuration" (Lovesh, L3.A166).

- an atom "which would be ... 2.8.7. would *need* another electron to have a full outer shell" (Tajinder, T1.A135)
- an oxygen atom "*needs* another two electrons" (Tajinder, T3.A318).
- "neon, has already, like it's got what it *needs*, the right amount of electrons to become stable, as it were" (Tajinder, T3.A318).
- neon "doesn't *need* to [lose or gain an electron] because it's already got a full outer shell" (Tajinder, T3.307).
- if an atom's outer shell was "full of like eight, then like, I don't think it would attract, because it would be full and it wouldn't *need* another electron" (Umar, U1.B464).
- carbon has "got a valency of four, 'cause it *needs* four electrons to fill up its outer shell" (Umar, U2.A238).

§A34.1.2: Incidental data.

Other examples of this use of 'needs' were found in incidental data collected from other chemistry students:

- the reaction between oxygen and hydrogen,"occurs because oxygen *needs* 2 electrons to join up" (induction exercise, September 1995).
- the reaction between oxygen and hydrogen "occurs because the oxygen atom is incomplete, it *needs* two extra electrons to complete its outer shell. Hydrogen is also an incomplete atom as it only has one electron in its inner shell, so in order to complete the inner shell it *needs* one electron (induction exercise, September 1995).
- "...chlorine atom *needs* one electron to complete an inert electronic configuration" (first year class-work exercise, January 1995).
- "Carbon *needs* 4 electrons while oxygen needs 2 electrons to complete its outer shell" (first year class-work exercise, January 1995).
- the bonding in sodium chloride is ionic "because sodium *gives* 1 electron (to complete its outer electron shell) to the chlorine, because chlorine *needs* to *accept* 1 electron to complete its outer shell" (response in A level mock, March 1994).

§A34.1.3: Carol, Debra, Kabul, Lovesh, Mike Tajinder.

A way of expressing similar ideas was in terms of the slightly less imperative reference to what an atom 'wants'. Again this was used widely amongst the colearners in this study,

- an atom could form "as many [bonds] as it *wants*, as long as it's got electrons to cover how many it does *want*" (Carol, C1.262).
- in sodium chloride, "because one's got an extra ... electron, and one ...

is electron deficient, so, they *want* to, get like erm, stable, they *want* to be like stable" (Carol, C2.305).

- chlorine is more electronegative than sodium so "it *wants* to grab hold of the sodium's like electrons, at a greater extent." (Carol, C2.171).
- once ionised, "the sodium will still *want* its electrons back" (Carol, C2.211).
- the carbon atom had "got four unpaired electrons, and so it *wants* to pair them off" (Debra, D2.667).
- "chlorine has got, you know, seven electrons in its outermost shell, so it *wants* to become a stable atom" (Kabul, K6.A322).
- a sodium atom "hasn't got a, a full outer - electron shell, outer electron shell hasn't got eight electrons in", so "it will *wanna* donate the electron to another atom" (Lovesh, L4.A067).
- aluminium chloride dimerises because "in $AlCl_3$, the aluminium hasn't got an outer, a stable outer electron configuration", and it "really *wants* to attract two electrons to become stable" (Lovesh, L4.A514).
- when an atom "has a full outer shield [sic] it's very unreactive" as it "doesn't *want* any more electrons in the outer shield, it's at its maximum capacity, of electrons" (Mike, M1.A206).
- sodium "*wants* to lose an electron, and chlorine *wants* to gain an electron to become a full outer shell" (Tajinder, T3.307).
- atoms "*want* to fill up, like electrons on each [orbital], to become like, stable" (Tajinder, T3.A318).

§A34.1.4: Incidental data.

This use of anthropomorphism was reflected in incidental data collected from other learners' course work. For example, one student explained at the start of the course that,

> "Magnesium has an electron arrangement of 2.8.2,so it *wants* to loose 2 e^-, while oxygen has an electron arrangement of 2.6, so it *wants* to gain 2 e^-. Now it is possible for Mg and O_2 to combine together to form magnesium oxide. The 2 electrons in the outer shell of Mg, go to the Oxygen so now Mg is complete with 2,8.
> (Induction exercise, September 1995.)

Other examples include,

- "the aluminium ion *wants* to have a full shell ie: 8 outer electrons" (end-of-first-year examination, June 1994).
- the second ionisation energy of magnesium was higher than the first ionisation because a magnesium ion was "less likely to *want* to stay as Mg^+ and so requires little energy to make it it become Mg^{2+}

from Mg^{+}" (end of first year examination, June 1994.) Unfortunately for this student, this is an example of a context where arguing from the FULL SHELLS EXPLANATORY PRINCIPLE predicts a different outcome to an electrostatic model, and the answer given contradicted the information provided in the question.

- "Na [sodium] *wants* to lose an electron" (first year assessment, February, 1996).
- "because it is a noble gas ie full outer shell therefore Neon will *not want* to lose these octet of electrons" (response to past examination question, first year, January 1994).
- "Neon's orbitals are full making it a noble gas the atom *doesn't want* to lose an electron because it wouldn't have the lowest energy state" (response to past examination question, first year, January 1994).

§A34.1.5: Incidental data.

For most learners there is probably little significance to the choice of 'needs' or 'wants', despite the literal difference in meaning, and the two terms can seem to be used interchangeably,

> "H atoms have 1 in their shell so they *want* to gain another 1 to complete their shell, so their [sic] is 2, while oxygen *need* 2 to form a complete shell of 8, so Oxygen combines with the 2 Hydrogen atoms to form, H_2O"
> (Induction exercise, September 1995.)

> "Hydrogen *wants* to gain an electron - and oxygen *wants* to gain 2 electrons to form a full outer shell of 8 - where as hydrogen only *need* to have two electrons in its outer shell to become complete - so the two hydrogen *share* their one electron each with the Oxygen & the Oxygen *shares* two electrons - one to each of the hydrogens"
> (Induction exercise, September 1995.)

§A34.1.6: Debra, Edward, Kabul, Mike.

Besides 'need' and 'want', learners used a number of other similar terms, such as 'like' and 'prefer', implying that atoms had human feelings. For example, among the colearners in the interview study,

- "some elements *prefer* to form molecules than exist as a single atom" (Debra, written comment, introductory course work task, September 1990).
- a covalent bond would hold atoms together "because they gain the full shell then, so they're stable molecules, so it's sort of *desirable* to be like that" (Debra, D2.111).
- atoms "*like* to achieve a stable noble gas configuration" (Edward, E1.231).
- the aluminium in $AlCl_3$ molecules "would *prefer* to have eight

electrons" (Kabul, K6.B135).

- "an atom *likes* to have the outer shield as complete as possible" (Mike, M1.A188).

§A34.1.7: Incidental data.

Once more, similar examples were found amongst other chemistry students, as in this explanation of the ionic bond in terms of electron transfer,

> "The bonding in NaCl is ionic. Ionic bonding involves the transfer of electrons from one atom to another. In this example Na is *willing* to *give* an electron to form a stable octet. ... The Cl is very electronegative and is therefore *very willing* to *accept* an electron to form a stable ion."
> (Mock examination response, March 1994).

Other examples are,

- "some elements *prefer* to form molecules than exist as a single atom" (induction exercise, September 1990).
- "a hydrogen atom is *very eager* to get the 1 electron to complete its outer shell and because oxygen *needs* 2 electrons to complete its outer shell, they *share* electrons in a covalent bond" (induction exercise, September 1995).
- Neon "has a full outer shell of electrons which it *likes* to stay that way" (end-of-first-year examination, June 1994).
- "Neon is an inert gas, in group 0 and *has no wish* to lose an electron" (end-of-first-year examination, June 1994).
- atoms "would either *prefere* [sic] to gain an electron in a bond or 'lose' it" (concept map, second year, May 1992).

§A34.1.8: Tajinder.

Tajinder sometimes referred to atoms *thinking*, and in particular that bonding took place so that the atoms could *think* they had full shells. Near the beginning of his first interview he explained the covalent bond in hydrogen in these terms,

> "It's where electrons are *shared*, by each, each of the shells, ... because this is the first shell it *needs*, two electrons to become stable, and, this only contains one so it ... joins with another hydrogen, and it *shares*, the other hydrogen's electron, so it, it *thinks* that it's got er, two electrons, then it becomes stable."
> T1.A111

This did not seem to be a 'slip of the tongue', as Tajinder reiterated the same point near the end of the interview (over an hour later),

> "in the hydrogen, to form an outer shell, a stable outer shell it *needs* another hydrogen, and so ... they have one each, they all *share* one, they all *share* both, so they both *think* that they have two outer electrons."
> T1.C208

In a later interview, in his third term, Tajinder again refers to the atoms in a hydrogen molecule *thinking* (and apparently just aborts before describing them as being *happy*),

> "they gain the two electrons, they share the two electrons, because they *wanna*, they *wanna* erm *think* of having noble gas configurations to become stable, so that's what hold them together. 'Cause if they, they can't actually move, if they move apart they're not having noble gas configurations, so they're not stable, and they do they don't *want* to be unstable, they *want* to be *ha*-, erm stable."
> T8.B587

Tajinder provided similar explanations in other interviews,

- "the carbon *wants* to gain a full outer shell, well so-called full outer shell, consisting of eight electrons, and erm, (one two three four), it already has four, so all it has to do is gain another four, so it can share, one, so it *thinks* it's got eight electrons, so if each electron shares with another electron, the carbon *thinks* it's got eight electrons, so therefore it's sort of stable" (T10.A348).
- in H_2SO_4, an oxygen atom has "got eight electrons in its outer shell, or so it *thinks*" (T12.C109), however, when considering the electrical neutrality of the H_2SO_4 molecule, "the oxygen *thinks* that its got 1, it's got 6 electrons, the other oxygen *thinks* it's got 6 electrons, and therefore hydrogen *thinks* it's got ownership of 1 electron and therefore it becomes stable as well" (T12.C127).
- in potassium fluoride, the fluorine takes the electron "completely away from the potassium, therefore *thinking* that it has electron which it has, which it has because the electron density is all shaped around the fluorine" (T12.D149).

As far as achieving full shells was concerned, Tajinder suggests that it is indeed the atom's perception of its octet status which is critical, so when aluminium chloride formed a dimer "the aluminium *thinks* that it's stable because it's got eight outer electrons, but really it hasn't, but it *thinks* that it has" (T10.A524).

§A34.1.9: Edward, Kabul, Mike, Noor.

Some colearners also talked as though the atoms then deliberately went about obtaining full electron shells:

- "atoms are, *happiest* when {laughs}, for want of a better word, when they've er, got full orbitals. And they always, that's what they always, *try* and, achieve" (Edward, E1.234).
- "an oxidising agent, ... *tries* to pull electrons away" from a sodium atom (Kabul, K6.A243).

- in hydrogen fluoride "fluorine is being *greedy, trying* to grab two electrons from two different areas, two different atoms" (Mike, M1.B115).
- in tetrachloromethane "the *aim* is *trying to* get the carbon, erm, outer ring full, and so you've added chlorine atoms to it, and they're all sharing, well they'll be *giving* one of their electrons to the carbon, so you've got four of them, and carbon's got four in its outer shell and it need another four to get, a complete shell" (N1.A100).

§A34.1.10: Incidental data.

Two further examples of learner statements about atoms 'trying' to obtain full shells may be quoted from students just starting out on A level,

> "most element apart from the one's [sic] in group 8 *try* to achieve a complete outer shell and *try* to lose or gain the outer shell status with a chemical reaction with another atom."
> (Induction exercise, September 1994.)

> "The outer electron shell, in all cases apart from hydrogen, has room for 8 electrons. Atoms will always *try* to change the no. of electrons to equal 8. e.g. oxygen has 6 electrons on its outer shell. Therefore it *wants* 2 electrons. The number of electrons that an atom *wants* is called its valency, e.g. oxygen has a valency of -2. Some atoms *want* to give away electrons. E.g. sodium only has 1 electron. Sodium has a valency of +1."
> (Induction exercise, September 1991.)

§A34.2: Anthropomorphism in other contexts.

In chapter 11 (§11.3.2) it is suggested that whilst anthropomorphic language was widely used in explanations based on full shells, it was also commonly used in other types of explanation.

§A34.2.1: Annie, Carol, Edward, Noor, Quorat, Tajinder, Umar.

The interaction between electrical charges was often discussed in anthropomorphic terms by the colearners,

- in a hydrogen molecule the electrons were "*trying* to get away from each other" (Annie, A4.227).
- the bonds in lithium iodide, hydrogen fluoride, and in iodine were "covalent, *trying* to be ionic" (Carol, C1.473, C1.536, C1.850).
- the bond between a sulphate anion and a cation would be "ionic but *trying* to be covalent" (Carol, C1.487).
- in benzene the hydrogens would "be up, down, like alternate" (C2.508) as they will "*try* and be as far away from each other as possible" (Carol, C3.510).

- the hydrogen molecule was stable because "it's just *happy* stopping there, not doing anything" (Edward, E1.217).
- "the electrons in the carbon, [are] all going to *try* and stay as further away as possible" (Noor, N1.A196).
- the four bonds around a carbon atom would "*try* and get as far away from each other as possible" (Noor, N1.A273).
- "the outer electrons in the valence shell of the atoms in the metals, get delocalised and they *swim* free, in the lattice"; "the valence electrons ... become delocalised and they *swim* around in the lattice" (Noor, N3.A035, N3.A449).
- positive and negative charges "move around all the time I think, *trying* to attract each other and then repelling each other" (Quorat, Q2.B426).
- positive charges "*wanna* come close to [negative charges], but they repel one another" (Tajinder, T1.B190).
- "the s-electron's free to move *wherever it wants*" (Tajinder, T6.B090).
- "the positive [ion] *tries* to get, like attract as many negatives as they can and vice versa, so as much as they can, like as many as can *cling on* to the opposite charge" (Umar, U1.B234).
- "polarisability is the 'willingness' of the anion to be polarised" (Umar, concept map on Chemical Bonding, June 1993).
- "when you heat [a metal], they, the positive ions vibrate, ... *try* to break free" (Umar, LU1.A447).

§A34.2.2: Incidental data.

Further examples of anthropomorphic language used to describe electrostatic phenomena were collected from the end-of-first-year examination given to A level chemistry students in the College in June 1994,

- "Cl's [sic] *want* to be as far away from the other Cl's but as close as possible to the B so they are 120° apart in a trigonal planar shape."
- "the bond angle [in NH3] is less than 109.5° because the three hydrogen atoms *want* to be a far as away from each other, with the 2 lone pairs of electrons present too."
- "BCl_3 is a covalently bonded molecule. Cl is negatively charged so the three Cl^- *want* to get as far away from each other (ie they repel each other) there for [sic] you get equal angles."
- "The ionic radius [of fluorine] is larger than the atomic radius because in the ionic radius you have more electrons *trying* to be nearer the nucleus."

§A34.2.3: Edward, Annie, Jagdish, Noor, Tajinder.

Chapter 9 demonstrated that learners may find some quantum ideas difficult to grasp, and this is another area where colearners in this study were found to use anthropomorphic language. So Edward described stability in the following terms,

> "that a particular species doesn't *want* to, it always *tries* to achieve its most stable, energy state, and it does this by, giving out energy. ... If it's stable it doesn't *want* to change to another form."
> E2.A198

Other examples of colearners discussing orbitals and energy levels in this way included,

- "the quantum shell, on what the electrons *sit*" (Annie, A1.186).
- "an electron always *tries* to achieve its ground state" (Edward, E2.A157).
- an electron "would absorb a photon of energy and be promoted to another vacant orbital and then it would *try* and achieve its stable state and give out that energy as light" (Edward, E2.A203).
- "if chlorine didn't form anions, and just ... *tried* to form a cation, that would require more energy" (Jagdish, J3.A197).
- an atom "*wants* to get to a lower energy level" (Noor, N3.A172).
- an atom "doesn't *want* to" have one electron in the s orbital and one in the p orbital (Tajinder, T3.A442).
- the lithium atom "*wants* to become lower energy, ... [and] it's like doing that by constantly losing an electron, well not losing but *giving* it away, *passing it around*, sort of thing" (Tajinder, T3.B131).

§A34.3: The extent of learners' awareness of their anthropomorphic language.

In chapter 11 (§11.3.3) it was suggested that in view of the widespread use of anthropomorphic language found in this research, it is important to know whether learners mean their anthropomorphic expressions to be literal or figurative.

§A34.3.1: Edward.

Edward used anthropomorphic language when asked to explain his comments about noble gas configurations. He explained that on "ionic bonding, and covalent bonding as well" atoms,

> "*like* to achieve a stable noble gas configuration. Which are, two in the first shell, eight in the second, and it goes up according to $2n^2$, depending on the shell."
> E1.231

He explained this with a tautology, that "each orbital in each shell is filled, and it doesn't *need* to acquire electrons, or, lose electrons, to fill all its shells" (E1.233). Edward was asked for further explanation. At first Edward seems to be going to repeat his tautology that the atom "doesn't require anything else" (E1.235), but he switches to an anthropomorphic response, that "atoms are, ***happiest*** ... when they've got full orbitals. And ... that's what they always, ***try and, achieve***" (E1.235). Edward considers that somehow atoms are aware of their electronic configurations, and are active agents in seeking full shells (E1.237), but is unable to suggest what form this awareness may take (E1.238-45).

I: And why is it, why is it so good having a full shell?
•••••••••••[pause, c.11s]
E: Because it's not reactive, it's inert. Doesn't ***require*** anything else to, it's, it's, er, elec¬ atoms are, ***happiest*** when {laughs}, for want of a better word, when they've er, got full orbitals. And they always, that's what they always, ***try*** and, achieve.
I: Right, so if you were a hydrogen atom, an isolated hydrogen atom, you would be aware would you, that you didn't have a full shell? And you'd be actively on the look out to do something about it?
E: Yes.
I: Ah, what kind of consciousness do you think hydrogen atoms have?
•••
I: How does the hydrogen atom know? Does it see it's only got one electron, or does it hear it? Or has it got some way of sensing the electric field? Or, has it got a little note book in its pocket?
E: {laughs}
I: You see what I'm getting at, I mean,
E: Yeah.
I: what kind of mechanism is there?
•••
I: And how would this atom know when it met something suitable for getting another electron, and how would it know when it [had] got two electrons in its full outer shell?
••••••••••••••••••••
E: I dunno.
E1.234

After the dialogue in this extract Edward was then asked if it is reasonable that atoms should somehow have a kind of awareness, and he still thought it was (E1.249), although he did not believe atoms could think (E1.253). On further questioning Edward suggested that "there has to be some mechanism" (E1.265) by which the atoms could form a molecule, and suggested "it must be something to do with the achieving a sort of equilibrium charge, force ... between the, particles" (E1.273). Edward still thought there was a requirement of the 'full shells' type, as "electrostatic" forces (E1.294) "would pull all the electrons in, closer to the nucleus, so that all these levels were filled, from the nucleus outwards", as,

> "in the atom [there are] defined orbitals and if the nucleus attracts the electrons, then there's going to be a vacancy outside the last electron to be attracted. And these ***need to be filled***"
> (E1.296).

§A34.3.2: Jagdish.

In Jagdish's third interview she was able to consider the stability of a sodium atom to be relative to its surroundings: its valence electron would not be removed unless there was some nearby agent to apply sufficient force (see below). However she continued to use anthropomorphic references, that the atom might *want* to form a lower energy level, and would *give* away its electron (J3.A345). Jagdish was asked whether 'that atom wants to form compounds', and she reiterated that it "wants to, yeah" (J3.A359). As Jagdish had just been applying an electrostatic framework to answer questions I was interested to find out whether her subsequent use of anthropomorphic language was just a habit of speech or amounted to an active explanatory framework. I asked a question posed in similar anthropomorphic language, (i.e. were there things the atom wanted to do even more than form compounds?) to see how the response would be framed. Jagdish initially seemed to ignore the anthropomorphism, and answered in terms of forces (which might suggest her anthropomorphic use of language was indeed habitual), but then concluded with a further anthropomorphism,

> "if you had a, another force in contact with it, and that force could have a significant effect on it, then I think this, atom would *want to* lose the electron and become an ion, but on its own, no, I think it's just *happy* on its own"
> J3.A359

I then attempted to test the extent to which Jagdish would continue to accept such language by presenting a range of alternative anthropomorphisms for her to accept or reject,

> I: Okay, I'm going to try and, erm, paraphrase, what we've just said, ... I mean we've said that erm, this particular species, although it's stable in certain situations *wants to* form compounds. So could I change that and say this species *likes to* form compounds, would that be true?
> • • • [pause, c.3s]
> J: Yeah.
> I: Erm, this species *desires to* form compounds?
> J: Yeah.
> I: This species *enjoys* forming compounds?
> J: {laughs} Yeah.
> I: Erm, this species *gets its kicks* forming compounds.
> • • • •
> J: Erm, yeah.
> I: Yeah? This species after due reflection and consideration, *decides* it would be a good idea to form compounds.
> J: Mm.
> J3.A367

As Jagdish appeared to accept all these alternatives, a further attempt was made to find the extent to which these terms were being used as metaphor, by challenging their literal meaning: I asked Jagdish how the atom knew it wanted to form compounds, had it been told, or had it worked it out for itself? Her answer alluded to physical interactions, but also suggested that the anthropomorphic frame was not problematic for her way of thinking about the atom,

> "At the moment because it's *on its own*, I don't think it ***knows*** that it *wants* to form a compound, but if you had, I think this is sodium right, but if there was another chlorine atom, in, like quite near it, and the distance was small enough to have, for the atoms to have an effect on each other, I think the sodium atom would *realise* that it could form a more stable configuration by giving one of the electrons to the chlorine and forming a bond, and so it would be at lower energy level."
> J3.A376

On this evidence, for Jagdish, the atom can ***know***, *realise* and *want*. Jagdish thought the sodium atom's realisation of the presence of a chlorine atom required close proximity, so "they actually have to come into contact, I mean like actual collision, has to happen, or ... they have to come so close" (J3.A385). The sodium "feels" the chlorine through the physical interaction, because

> "you're going to have some kind of attraction ... Or repulsion. You're gonna have some force. The chlorine is going to have some effect on the sodium. The sodium is going to have an effect on the chlorine. So it's going to *feel*"
> J3.A385

Despite this 'feeling' Jagdish did not think a sodium atom would make a conscious decision to interact with another species, Jagdish did not "think it stops and thinks, I think it just happens" (J3.A432).

Later in the interview, the extent to which the atom had feelings was revisited. Jagdish agreed that the atom ***desired*** to form a compound, although she did not think it got lonely (J3.A508). Whether the atom would get jealous "depends on how, reactive that particular ... atom is compared with the, other atom that has formed a compound" (J3.A508). A hypothetical example was given of a sodium atom that is left after some sodium reacts to form sodium chloride, and in this case the atom,

> "probably does [become jealous] but it can't do anything about it because it's ... as reactive as the sodium that's formed the compound ... [whereas] if it was a more reactive element it could replace, displace the sodium and form a compound with the chlorine"
> J3.A508

Jagdish suggested that a particular atom getting left out was just "chance" (J3.A520). She agreed it might feel envious, but then added the caveat "if you can say that about an atom" (J3.A520). Jagdish did not think the atom would feel hate, and at this point decided the atom had "no" feelings, "none" (J3.A520).

However, later in the interview, Jagdish referred to how an iodine atom "has to have eight to be more stable" (J3.341). I asked her if the atom 'would *prefer* to have eight', and would 'it *want* to have eight', and she agreed to both these alternative suggestions, and that 'it *wants* to get the lithium [atom]'s electron' (J3.B352). Once again Jagdish was quite comfortable with the use of anthropomorphic description, but when the sentience of the atom was queried she said that "it doesn't know" that it needs another electron (J3.B355). Rather, "if it had eight, it would be a lower energy level, ... it would be more stable, and so you would need more energy to actually disrupt it, to make it into something else" (J3.B355). So at this point Jagdish seemed to have rejected a literal meaning to the anthropomorphic language once again, and to be focussing on something more physical, *i.e.* energy levels. However, when asked why a bond should form, Jagdish explained that "if they formed a bond they would both be at a lower energy level, and that's what they all *want*" (J3.B361). What they all wanted, according to Jagdish, was "to form a more stable compound, more stable species" (J3.B361). Once again Jagdish had switched back to anthropomorphic language, and once again I challenged her by asking how the iodine atom knew it was not at a lower energy level, with eight electrons. Again this led to Jagdish focussing on a physical mechanism, *i.e.* forces, as "when the iodine comes close to it, it has a force on it" (J3.370). However, she was only able to offer a teleological explanation for why there would no effect on the stable species: that

> "if the lithium was at a lower energy level, and it was already stable, ... [then] no matter how close the iodine came, there would be no effect, ... on the lithium ... 'cause if it was already a stable compound, if it was already a stable species, *what's the point* of it being attracted or repel, repelled or whatever?"
> J3.B370

At the very end of the interview Jagdish used a similar type of teleology, when her comments she had made earlier about the hydrogen molecule were being followed up. Jagdish thought that if the electron in a hydrogen molecule was at the same average distance from the nucleus as in an atom "then there wouldn't be a point, any point in forming a bond ... in forming the compound" (J3.437). By this stage in the dialogue she had considered the molecule in terms of the forces between the components, and on reflection she decided "it's the same distance as before, because all the atom *wants* to do is ... it just *wants* to erm, neutralise the core charge" (J3.B437). This was the last episode in the interview, which therefore concluded with Jagdish referring to electrostatic factors, but in terms of an anthropomorphic framework of language.

§A34.3.3: Kabul.

During Kabul's fifth interview he referred to the delocalised electrons in a metal in an anthropomorphic way, although he realised this and corrected himself,

> "...the outer orbitals...tend to overlap...with one another, they form a massive...band of electrons, and the electrons can just ***wander around*** {laughs}, no, it ***appears*** to be electrons just wandering around, it's just electrons, electrons, electrons, you know.... It's ***not really*** wandering around, you know, but, it just looks like that..."
> K5.A206

Kabul also seemed aware of his use of anthropomorphism when considering the purpose of hybridisation,

> "if it is in the same energy level, take p, p orbitals, then all of them can get all hybridised ***if they want to***. If they are [able to] obtain a {laughs} stable structure by not hybridising they can just hybridise partially. ... It depends what ***they want*** to form, like you know, if ***they want*** to form ... like example methane, you know, ***they need*** four bonds, so they form sp^3 hybridisation, when in ethene, for example, ***they need*** two, two bonds for hydrogen, and two bonds for carbon so they could undergo sp^2 hybridisation."
> K5.A347

Although Kabul claimed that this use of "wants" was not literal, but "just theories ... to make our life simpler", he was satisfied with level of description,

> I: How does the carbon know whether it wants to form methane or ethene, say?
> K: It doesn't, it's just theories which we, you know, just to make our life simpler, we just, you know, say.
> I: We just say it do we?
> K: Yeah.
> I: Oh. Okay, right. So erm, so the kind of hybridisation it gets depends on what it wants to form?
> K: Yeah.
> I: Yeah, you're happy with that?
> K: Yeah. {laughs}
> I: Okay.
> K5.A361

It is not clear whether the degree of metacognitive awareness Kabul had of his use of "they want" also extended to his use of "they need" in the passage quoted. Another use of 'wants' occurred when Kabul was considering how dative bonds form in aluminium chloride, and he suggested that chlorine "has got lone pairs of electrons which it can donate anywhere it *wants*" (K5.B262).

In his final interview, during the last term of his course, Kabul referred to stable species being 'happy',

I: Why is number 2 stable?
K: 'cause all the, you know, outer electrons are, have got, you know, paired electrons, so everything is *happy*, stable.
I: They're happy are they?
K: Yeah.
I: Yeah? Erm. How do you think they celebrate when happy?
K: They just don't react.
I: They just don't react?
K: Yeah.
I: Oh, okay.
K6.A200

Kabul did not seem to find this level of description as inappropriate, nor the question about the mode of celebration as problematic. Later in the interview Kabul referred to how "an oxidising agent, ... *tries* to pull electrons away" from a sodium atom (K6.A243), which is "quite *happy* to give it away, because it comes more stable" (K6.A246), and how "an oxygen atom, ... has got six outer electrons ... so they, each oxygen, has *needs*, ... [for] 2 electrons to become more stable so you know they form the octet" (K6.A243). Kabul's notion of atomic happiness was queried,

I: Erm, I think you said the sodium atom was quite happy to do this,
K: Yeah.
I: 'cause it can get stable as well?
K: Yeah.
I: So is the sodium atom aware that it's not stable at the moment?
K: Yeah.
I: Yeah, and it would be aware when it became so, when it became stable?
K: Yeah.
I: Yeah? What kind of awareness is this, how does, what [form] does this awareness take?
• • • • • • • [pause, c.7s]
K: Don't know.
I: You know if we're talking about an awareness, is it, is it consciousness? Is it the same sort of thing?
K: No.
I: No?
K: No.
I: Does it think in words, like we do?
K: No.
I: No? So it wouldn't verbalise it?
K: No, no.
I: It wouldn't say 'oh look, eleven electrons, no that's no good'?
K: {click, click} It just happens.
I: It just happens.
K: Yeah.
K6.A259

So the atom *was* aware, although not consciously so, rather "it just happens", as if by magic (indicated by the clicking of Kabul's fingers). Kabul then decided the atoms were "not really" aware, and reiterated that "it just happens" (K6.A268).

The argument appeared to be that the less electrons that have to be gained, the more likely this is to be achieved, and therefore the more electronegative the atom.

Later Kabul said that a single atom of iron would be stable, whereas a single atom of sodium was not (K6.A416), and this was because "sodium is more electropositive than iron so it tends to lose electrons more readily" (K6.A418). Kabul explained that this difference in electropositivity was,

> "because iron has got 'd' electrons, you know, a lot of 'd' electrons in there, and er, • • • • and in sodium they're just 's' electrons, there's just one electron in its outermost shell. So it's easier for sodium to lose just one electron and obtain its octet state, whereas in iron, since there are, I don't know how many electrons in the d-orbital, but it's difficult to lose all the electrons, you know."
> K6.A426

This seems to be formally the same argument as used for electronegativity, so that the less electrons that have to be lost (c.f. gained), the more likely this is to be achieved, and therefore the more electropositive (c.f. electronegative) the atom.

Later in the interview Kabul referred to how a dative bond would form between $AlCl_3$ molecules "to obtain the octet state because octet state is usually stable" (K6.B128). The molecule knew it had not got an octet state as "it's unstable, it's not aware, you know, physically, but, you know, it would *prefer* to have eight electrons" (K6.B135). Kabul thought that 'prefer' meant something "different" (K6.B135) for atoms than for people, but he was not able to explain this any further.

Appendix 35.

Evidence of octet thinking: the history conjecture.

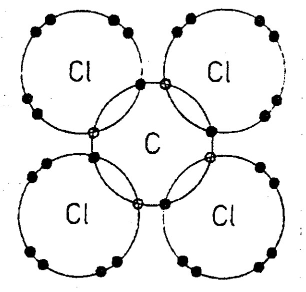
§A35.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.4.

§A35.1: Bond fission.

In chapter 11 (§11.4.1) it is suggested that when colearners discussed bond-breaking in contexts such as focal figure 3, they sometimes specified that the electrons would return to the atoms from which they originated.



focal figure 3

§A35.1.1: Jagdish, Edward, Kabul, Mike, Paminder, Quorat, Tajinder.

For example, Jagdish suggests that when a bond in focal figure 3 breaks,

> "the chlorine would go back to being an atom, so it would acquire one of those electrons that *it gave in the first place* to form the bond, so ... it would probably take this [indicating an electron on diagram], because seeing as that's *the one from the chlorine*."
> J3.B104

Other examples from the interviews were,

- "the chlorine would leave with ***its own*** valence electron, and the carbon atom would keep its, ***its own*** valence electron" (Edward, E1.342).
- the two electrons "will get back to their original shells", that is "the black one will go to chlorine and this round one will go to carbon" as "the black one is ... [an] electron of chlorine, while the round one is the electron of carbon" (Kabul, K1.A263).
- "homolytic fission, that's like chlorine free radical, where *each of the chlorine gains back its electrons*, the shared electrons come back to each of them" (Kabul, KT1.A081).
- "one of the electrons would go to carbon and one of them would *go back* to chlorine ... the one which originated from chlorine would go to chlorine, while the one which originated from carbon would go to carbon" (Kabul, K4.A353).
- "the filled in [electron] would *stay with* the chlorine, and the clear one would *stay with* the carbon atom" (Mike, M1.A324).
- "it could be that the *chlorine electron* stays with the chlorine, and the *carbon electron* stays with the carbon" (Paminder, P1.A432).
- the carbon "electron would return to its ***own*** one, ***own*** nucleus, and the chlorine electron would be returned to its ***own*** atom" (P3.A428).
- "the chlorine [electrons] would go on the chlorine, and the carbon [electrons] would go on the carbon" (Quorat, Q1.A363).
- although all electrons were the same (T1.A237), "the chlorine electron would stay with, the chlorine atom, the carbon electron would stay with the carbon", because of "which electron *belongs* to which" (Tajinder, T1.A266).

§A35.1.2: Kabul.

In Kabul's first interview he knew "there wasn't any difference" between electrons, but confirmed that they would go back to the 'right' atoms (K1.A270). Although he accepted that the "atom has no idea" which electron to take back, Kabul thought it would get the 'right' electron back (K1.A274). However, by the end of the first year of his course, Kabul had constructed an explanation for this phenomenon, based on electron spin, that,

> "electrons are in [orbitals], you know, first they spin parallel to each other, and these atoms, you know, are opposite spins, so if carbon takes one of the electrons of its own, which is, let's say, having an, you know, a spin position of plus half, and if it takes one of the electrons from chlorine, which has an opposite spin, so it's s [spin-quantum number] will be minus a half, and that's against, you know, Bohr-aufbau's principle, you know, to do that."
> K4.A364

This explanation was quite ingenious, although ultimately invalid, as on breaking one bond there would no a priori reason why a carbon radical with an electron of either spin state would be lower energy.

§A35.1.3: Mike, Paminder, Quorat.

Several of the colearners were found to explain why an atom would 'get its own electrons back' on bond fission in terms of there being greater force between a nucleus and its own electrons. In Mike's first interview for the research he suggested electrons might be represented differently in diagrams of molecules "to show which electrons *belong to* which atom", so in focal figure 3 "the clear circles belong to the carbon, the filled-in circles belong to the chlorine atoms" (M1.A133). This was significant for Mike, as although an electron in the carbon-chlorine bond would be "attracted to both the carbon and the chlorine atom", one of the electrons in the bond would be "most attracted to the chlorine atom" and the other would be "more attracted to the carbon than the chlorine atom" (M1.A155). Later he explained that one electron would be attracted "more to chlorine nucleus as [it] originated in that atom to start off with", whilst the other electron was attracted "more to the carbon" because "that is the original atom that it started off with" (M1.A244). Further if the bond was broken the electron that "*belong* to the chlorine" "would *stay with* the chlorine, and the" electron that "*belong to* the carbon" "would *stay with* the carbon atom" (M1.A324, M1.A133).

In her first interview Paminder suggested that when a carbon-chlorine bond was broken "it could be that the *chlorine electron* stays with the chlorine, and the *carbon electron* stays with the carbon" (P1.A432). Paminder's reasoning was that, "the proton in the chlorine nucleus, they're attracted to that {poking diagram} particular one, in its own outershell, its not attracted to that carbon, carbon's electron" (P1.A444). Paminder accepted that "it could be possible like, you know when they're bonded, ... there *might* be an attraction" for the other electron, (P1.A444), however she thought that if the bond was broken the carbon atom "will *keep its electron*, and the chlorine will *keep its electron*, 'cause it's got a *stronger attraction* with that one" (P1.A444).

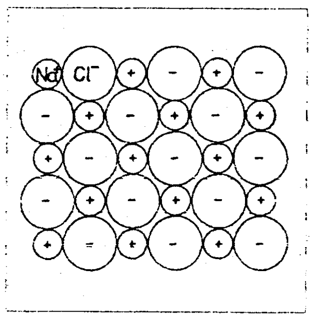
In her third interview Paminder said that in the hydrogen molecule "both nucleuses [sic] attract that electron and this electron" (P3.A267), although each electron would be attracted most by "the one which it's come from" (P3.A275). When she was asked why this was Paminder thought for some time (about 18 seconds) before suggesting, "I wonder if it's closer, slightly closer to that nucleus, I'm not sure, the one which it comes from" (P3.A275). Later Paminder suggested that in the carbon-chlorine bond in tetrachloromethane "the chlorine or the carbon might attract different ... electrons, differently" (P3.A341). She again suggests the electrons may be closer to their 'own' nuclei, although it is not clear if she sees this as cause or effect of the differential attraction,

> "Would the carbon one attract its own electron more closely, and the chlorine would attract it's electron more closely? Although it will attract the other one as well, but *not as much as it attracts its own one* ... There's a *greater attraction for its own electron* I think because it's slightly more closer to itself than the other one."
> P3.A356

Paminder said that if someone suggested that as both of the electrons were in the same bond, they must both be the same distance from the carbon nucleus, and they must both be the same distance from the chlorine nucleus, she would "probably argue with it" as she still thought "that the carbon's own electron is closer to it" (P3.A422). Paminder thought that if the carbon-chlorine bond was broken, then the carbon "electron would return to its own one, own nucleus, and the chlorine electron would be returned to its own atom" (P3.A428). Paminder did not think the electrons were likely to end-up the other way round "because it would seem a bit of an odd-ball wouldn't it, to have somebody else's electron" (P3.A428). She did not think both electrons were likely to go to the chlorine atom either, rather it was more likely that "each electron returns to its own atom" P3.A428).

In Quorat's first interview for the research she also demonstrated a belief that electrons would be attracted more to the nucleus of an atom where they originated. She said that if the carbon-chlorine bond in tetrachloromethane was broken then "the chlorine [electrons] would go on the chlorine, and the carbon [electrons] would go on the carbon" (Q1.A363). The electrons returned "where they originally came from", and they did this "because the forces on the carbon [electron] are greater from the positive nucleus of the carbon than they are - from the chlorine" (Q1.A364). The electrons in a carbon-chlorine bond were attracted to both nuclei, but one "more by chlorine" and the other "more by carbon" (Q1.A364). Quorat was not sure why this should be, but suggested this was because "it originally came from that" (Q1.A364).

§A35.2: Ionic bonding seen as electron transfer.



focal figure 5

In chapter 11 (§11.4.2) it is suggested that in the research it was found that mention of ionic bonding to learners was most likely to elicit comments about *electron transfer* to *form* ions, in addition to, or in precedence to, or even in place of, consideration of the electrostatic forces between ions.

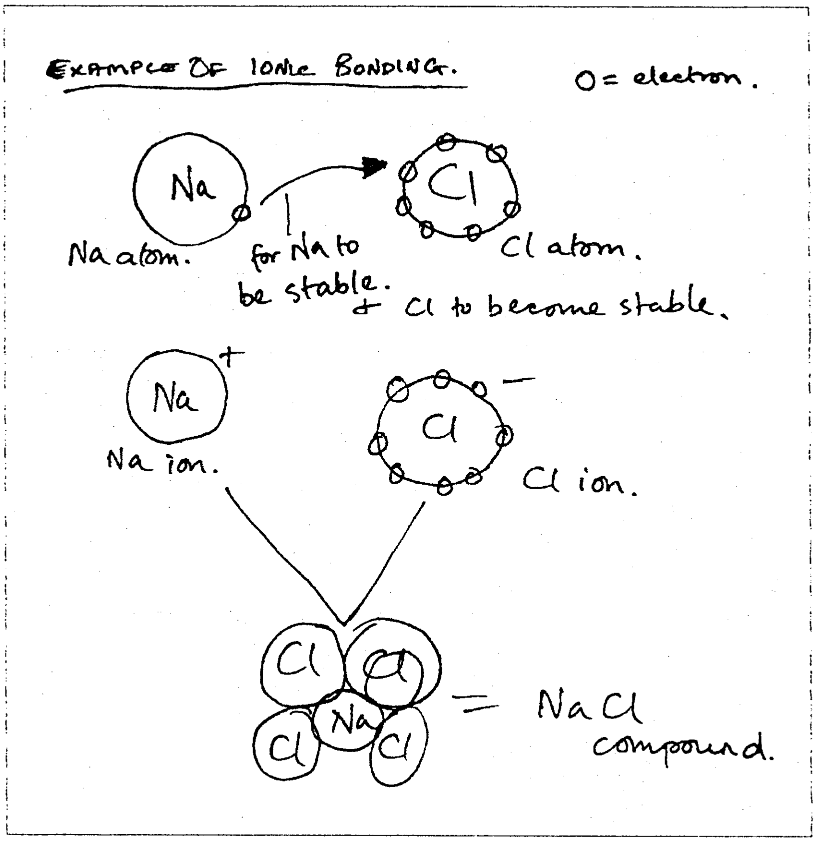
§A35.2.1: Brian, Carol, Debra, Jagdish, Kabul, Lovesh, Noor, Paminder, Quorat, Tajinder, Umar.

In Brian's first interview he explained the ionic bond in terms of electron transfer, that is "the electron from the sodium has been transferred to [the chlorine-minus], and that's got the electrons which makes it negative, whereas sodium hasn't, so ... becomes positive" (B1.254). Carol saw the ionic bond, not as the electrostatic force, but rather as the "complete transfer of an electron, to, another atom" (C2.205). It was "a complete transfer of electron, of electrons to the other ... substance, and ... the greater the difference in electronegativity, ... the more the bond tends to be ionic" (C2.289-91). In Debra's first interview she defined an ionic bond as "when one electron's lost from an atom, and given to another atom" (D1.672).

When Jagdish was asked to explain ionic bonding in the first interview she did this in terms of electron transfer and ion formation,

> "sodium atom *gives* one of its electrons to the chlorine atom. So sodium has more protons than electrons at the moment so it becomes a sodium ion with a charge of +1. And the chlorine atom has more electrons, one more electron than protons, so it has a charge of -1. So it's a negative ion".
> J1.A223

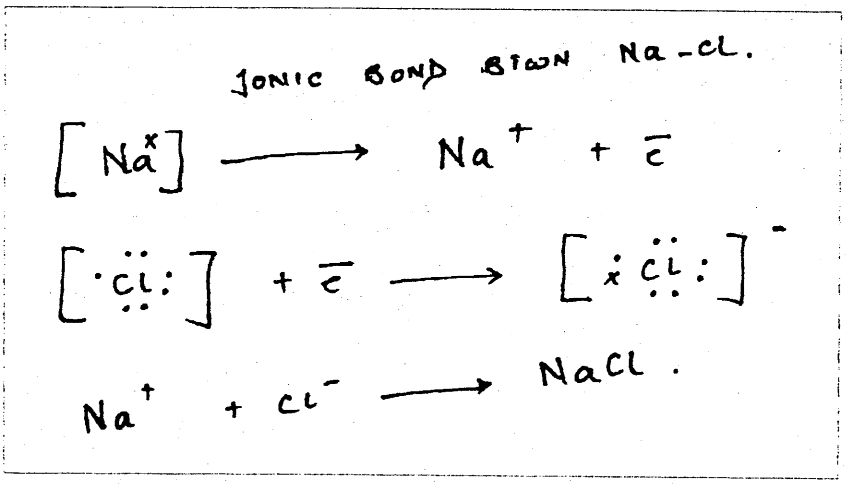
She summarised ionic bonding as "when atoms *gain* or *lose* electrons, and become ions" (J1.A238). In other words she did not refer to the bonding itself, but rather the process of electron transfer that led to ion formation. Later she reiterated that ionic bonding was the "*transferring of electrons* from one atom to another" (J1.A278). During the first term of her course Jagdish was asked to list, and then try to draw, the different types of chemical bond she knew about. Her figure for ionic bonding is reproduced (reduced) below. In the diagram, the process of electron transfer has a major role, and the rationale for electron transfer is "for Na to be stable. & Cl to become stable."



Jagdish's diagram for ionic bonding, November 1992.

In a concept map, Kabul drew as an introductory exercise at the start of the course, he described the formation of ionic bonding as "loss or gain of electrons from anions [sic]" (concept map on 'chemical bonding', September 1992), focussing on the process of ion formation, rather than on the bonding. In his first interview Kabul describes the chemical bonding in focal figure 5 as "an ionic bond", which is "a bond formed when an atom loses or gains an electron". He goes on to describe how, on the figure, "over here as you can see sodium has lost an electron, while chloride, chlorine has gained *that* electron, so this makes it a form of sodium chloride. An ionic bond" (K1.A154).

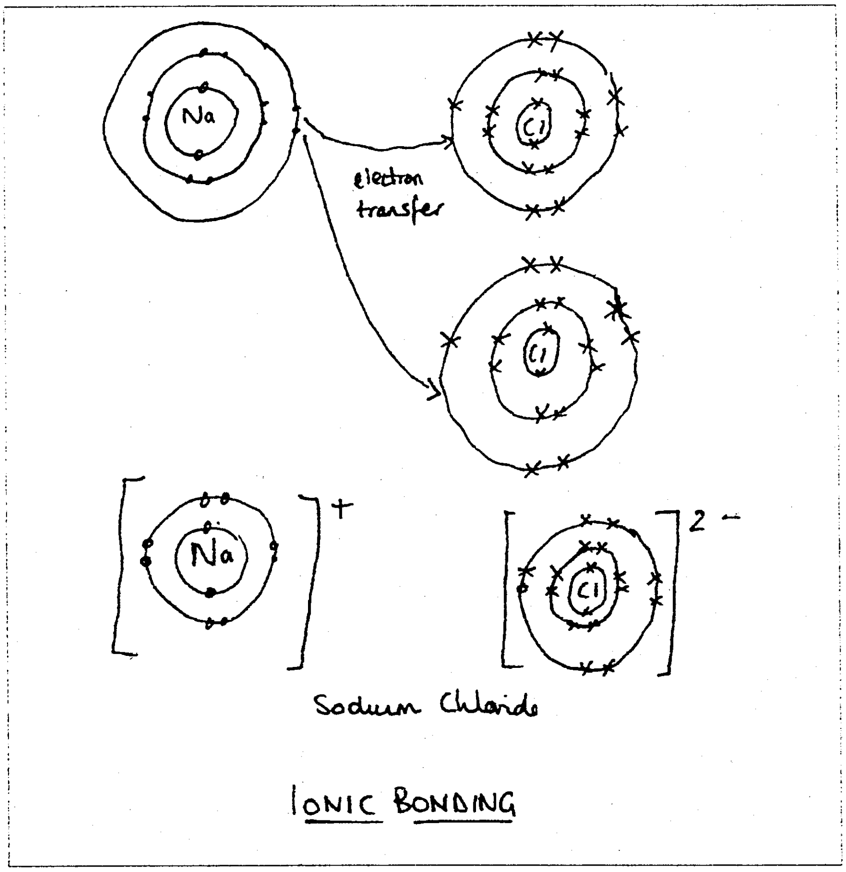
Later Kabul reiterates that ionic bonding "is formed when electrons are lost or gained *between* two atoms" (K1.A395), and later still in the interview, he explained that electrons were needed for ionic bonds "because one of the atoms has to lose an electron while the other has to gain" (K1.B156). Later in the term when he was asked to draw a representation of the different types of bond he was familiar with, Kabul drew the ionic bond between sodium and chlorine as a three stage scheme: emphasising ion formation (although not *explicitly* electron transfer) from sodium and chlorine *atoms*:



Kabul's diagram of ionic bonding, November 1992.

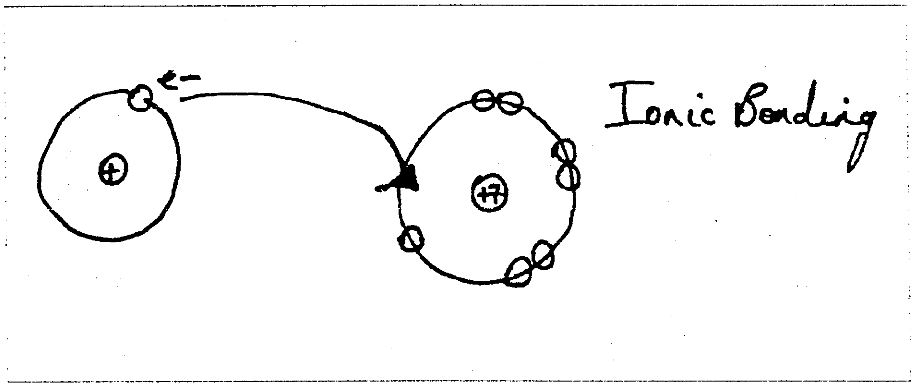
In his second interview Kabul again explained ionic bonding in terms of electron transfer. He gave "sodium chloride" as an example of an ionic material (K2.A118), and he explained that "sodium loses an electron, and chlorine gains an electron. There's a loss and gain of electrons between sodium and chlorine" (K2.A118). Later in the discussion Kabul reiterated that sodium chloride was held together by "ionic bonding", which was a "bond between two atoms, where an atom has lost an electron while other has gained an electron" (K2.A304). So for Kabul an ionic bond was obtained "when an atom loses an electron, while the other atom gains the electron" (K2.A322), so in the reaction between sodium and chlorine the "sodium atom has just lost an electron, while the chlorine atom has gained one electron" (K2.A336).

In Lovesh's first interview for the research he defined ionic bonding as "where you, donate, or gain electrons, to form a, completed outer shell" (L1.A308). In a diagram he drew during his first term of the course, Lovesh represented ionic bonding in terms of electron transfer. Lovesh showed some confusion over the valencies involved, but as electrons are shown donated to two separate chlorine *atoms* (not a molecule), this only serves to emphasise how he construed the ionic bond as electron transfer between isolated atoms. Lovesh also shows the product ions with their stable electron configurations.



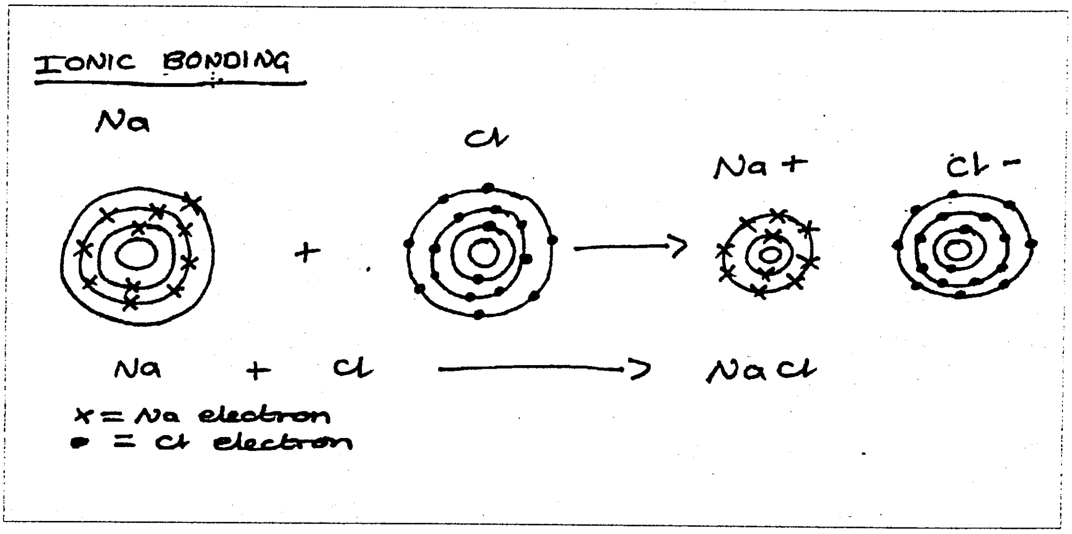
Lovesh's diagram of ionic bonding, November 1992

In Noor's first interview for the research she explained ionic bonding in terms of an electron transfer event, where atoms attempted to satisfy the octet rule explanatory principle, that is "ionic bonding is the *transfer of electrons* from one atom to another, and it, the aim again is to try and get, erm, complete outer shell" (N1.A300). During her first term she depicted ionic bonding as an electron transfer event between isolated atoms,



Noor's diagram of ionic bonding, November, 1992.

In Paminder's first interview for the research she suggested that in focal figure 5 the species were, "linked ionically, because a sodium atom has one electron in its outer shell, and the chlorine atom has seven electrons in its outer shell, and for both of them to become stable, the Na atom *gives* its one electron to the Cl atom, so now the Na is stable and so is the Cl" (P1.A207). This explanation again ignores the actual bond in sodium chloride, and focuses on a conjectured electron transfer between sodium and chlorine atoms, to give them full outer shells. She explained that ionic bonds were different to covalent bonds as in covalent bonds "the electrons are shared, and ionic bonds are when electrons are *transferred*" (P1.A216). Early in her second term of the course Paminder drew a depiction of ionic bonding, where she represented the process of ion formation between isolated atoms of sodium and chlorine, to give an ion pair:



Paminder's diagram of ionic bonding, January 1993.

In a concept map prepared as an introductory exercise at the start of the first year of Quorat's course, she demonstrated that she conceived ionic bonding in terms of the FULL SHELLS EXPLANATORY PRINCIPLE, and saw the transfer of electrons as integral to the bond,

> "Ionic bonding involves *electron transfer*. ... Ionic compounds, they try to make both elements stable by ensuring they have full outer shells."
> (Concept map on chemical bonding, September 1992)

In Tajinder's first A level chemistry lesson he prepared a concept map on chemical bonding, which included the proposition that "transfer of electrons takes place in ionic bonding" (September 1992). In his first interview he described ionic bonding as "where the sodium atom loses the electron to the chlorine atom" (T1.A446).

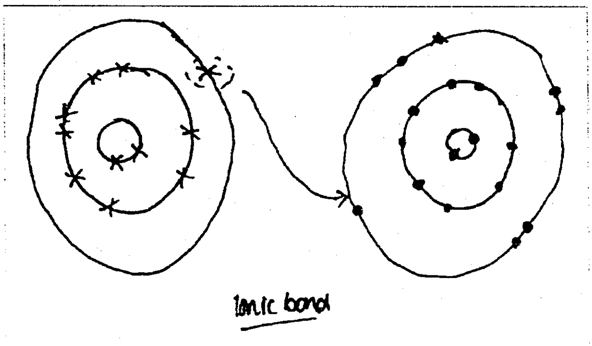
A little later he expanded on this,

> "if we take sodium and chlorine, ***an ionic bond is where the sodium lose ... one electron on its outer shell to the chlorine*** which contains seven on its outer shell, ... so, like, they are bonded. They're ionically bonded. So, ionic, can define it as, ***ionic bond is where, an atom loses its outermost electron, to, ... another atom*** which needs one electron in its outer shell to ... become stable.
> T1.A481

At the end of the interview Tajinder recapped some of the key points. His explanation of the ionic bond included the forces between charges, but still focussed on the conjectured electron transfer event,

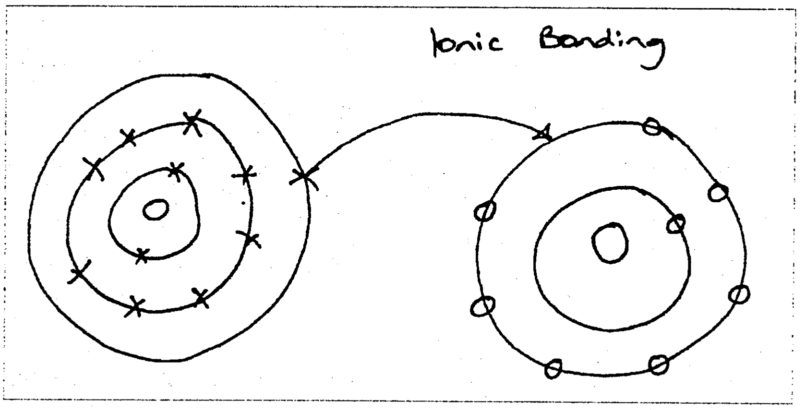
I: And in ionic, what is the bond in an ionic substance?
T: Er. The *transfer of one electron to, from one ... atom to another.*
I: So there's an attraction between different atoms because?
T: Of the transfer of electron, or electrons.
I: Right, the *transfer of electrons* and that gives rise to a bond which holds the thing together.
T: 'Cause ..., *also* forms a positive and negative, because like as one loses electron it might form a positive, and as one gains, it forms a negative. Positive-negative.
I: Positive and negative.
T: Attractions.
T1.C208

If Tajinder's use of 'also' can be taken literally, then he was not suggesting that electron transfer was just the means by which 'positive-negative attractions' came about, but rather he seemed to be suggesting that the 'positive-negative attractions' were a 'bonus', an almost fortuitous side effect, of ionic bonding. Later in his first term Tajinder was asked to draw diagrams of the types of bonding he was familiar with. His diagram for ionic bonding showed just two atoms, and indicated the process of electron transfer between them.



Tajinder's figure of ionic bonding, November 1992.

In Umar's first term of A level chemistry he drew a diagram representing his understanding of ionic bonding. His diagram also indicated the transfer of an electron from one atom to another:



Umar's figure of ionic bonding, November 1992.

It may be seen that there are a number of common features of the colearners' explanations of the ionic bond near the start of their A level courses. The ionic bond was generally seen as an electron transfer event between discrete atoms, to give ions with stable electronic configurations. The colearners' discussions of ionic bonding are consistent with the FULL SHELLS EXPLANATORY PRINCIPLE, and are conceptualised in terms of discrete atoms (i.e. making an assumption of initial atomicity, §11.1.1).

§A35.2.2: Kabul.

In chapter 11 (§11.4.2) it is suggested that Kabul only thought two ions could attract if there had been electron transfer between them. In his third interview Kabul said that if a sodium ion and chloride ion in solution came very close "it's not possible" that they might attract and stick together as "attraction is only possible when a bond is formed" (K3.A056),

> "The attraction is only possible when a bond is formed, you know? When we take ... sodium metal and chlorine gas. When you mix them, when you react them. At that time when a bond is formed, only at that time, sodium and chloride ion will join together. There should be some bonding between them, to hold them"
> K3.A056

Kabul was presented with a hypothetical universe that consisted of a sodium ion, and a chloride ion, a short distance (50 nm) apart. He did not think there would be any attractions nor bonding between the ions (K3.A070). According to Kabul a bond could *only* be formed if there was an electron transfer event, "when at the same time, when metal loses an electron, and at the same time the gas gains an electron, then a bond can exist between them" (K3.A070). Kabul was now presented with two such hypothetical universes ("both of them contained one sodium ion, and one chloride ion, and they were at a distance of ... 50 nm") that seemed identical, but had different 'electron histories', and he perceived that this would make a difference to the interactions present,

I: In one of these universes, if you knew about the history of the universe,
K: Yeah.
I: you would realise that the universe was created with a sodium ion and a chloride ion.
K: Yeah.
I: In the other universe, you'd find that wasn't true. There was a sodium atom and a chlorine atom. And that an electron has been transferred.
K: Yeah.
I: So tell me about these two erm, universes.
K: The one where we just found a metal, you know, where sodium atom has lost an electron, and chlorine atom has gained the electron, for that there would be an attraction between sodium ion and chloride ion, because there is a bond between them. But over there ... I don't think so there will be an attraction.
I: No, so you, there's a difference between them?
K: Yeah.
K3.A094

Again Kabul suggests the existence of a bond does not depend on electrostatic attraction, but the electron history, so that "where sodium atom has lost an electron, and chlorine atom has gained the electron, for *that* there would be an attraction between sodium ion and chloride ion, because there is a bond between them" (K3.A106). In fact Kabul did not think it was possible for a universe to be created with ions rather than atoms (K3.A130, see chapter 11, §11.1). Nevertheless, he did *not* think a bond would be formed if a positively charged ion and a negatively charged ion, that were already charged, were placed next to each other (K3.A131).

§A35.2.3: Carol, Jagdish, Kabul, Lovesh, Noor, Paminder, Umar.

In chapter 11 (§11.4.2) it is suggested that there is evidence from the data collected that colearners often continued to see the ionic bond - at least primarily - in terms of electron transfer between discrete atoms, after they had been taught during their A level course that the bond was an electrostatic interaction between ions.

Carol retained the 'octet' definition to the final interview near the end of her course, when she defined the ionic bond as "complete transfer of, an electron, to another atom" (C3.646). In Jagdish's third interview, near the end of her first year, she described ionic bonding as "when more or less an electron is *transferred* from one ... atom to another, so it ... can come to a lower energy level, more stable" (J3.A110). Later she explained that in focal figure 5 there was ionic bonding where,

> "you've got complete *transfer of electrons*, instead of just sharing, and because you've got complete *transfer* ... if you just looked at one particular, species in the bond, you could tell it's got a charge on it, because there's been a complete *transfer of electron*, either to itself, or it's *given* it, 'cause ... if you look at the sodium, it's *given* electrons, so it's got a plus charge, whereas the chlorine's *taken* that electron, or an electron from another sodium or something, and so it's got a negative charge, so you've got, so you've got the electrostatic forces *as well*."
> J3.B218

Although electrostatic forces feature in the answer, they appear as almost an afterthought ("you've got the electrostatic forces *as well*"), and Jagdish's focus of concern here certainly seems to be the transfer of electrons.

At the start of his fourth interview (near the end of his first year), Kabul referred to ionic bonding in terms of the electron transfer event, that "there is ionic bonding, which occurs when there is loss and gain of electrons" (K4.A043). When focal figure 5 was considered Kabul recognised "ionic bonding" (K4.A512) which was again explained as when "one of the atoms loses its electrons and the other atom gains that electron" (K4.A512). In the final interview, during the last term of his course, Kabul once again explained ionic bonding as where "one of the atoms loses the electrons, another atom accepts the electrons" (K6.A390). He described the bond in one figure (focal figure 9) as being "an ionic bond" (K6.A462), as "fluorine attracts the electron completely from potassium, so there are no... outer electron around potassium any more, they're all around the fluorine atoms, so [potassium] has completely lost the electron" (K6.A465). Kabul uses the language of electrostatics, but still focuses on the electron transfer event, rather than the bond that results.

Lovesh continued to define ionic bonding in terms of a conjectured electron transfer event through out his A level course. So in an interview near the end of his first year he explained that "an ionic bond is when one atom transfers electrons to another atom, completely, to form positive cation and negative anion" (L3.A025). When he prepared a concept map as an end-of-year revision exercise he wrote that "ionic bonding involves the complete transfer of electrons" and "ionic bonding ***results in*** the formation of cations and anions" (concept map on chemical bonding, June 1993, emphasis added). From the CURRICULUM SCIENCE perspective it would have been more correct for him to have said something like 'ionic bonding occurs as a *result of* the formation of cations and anions'. In an interview during his last term of the A level course Lovesh explained that, "in covalent bonding you've got the actual sharing of electrons, between atoms, but in this [ionic lattice of sodium chloride], you've got ... electrons being *donated* to other atoms, forming positive and negative ions which are attracted to each other" (L4.A266).

By the end of Noor's first year of A level study her explanations of ionic bonding included electrostatic ideas, but although the ionic bond is no longer said to *be* electron transfer, Noor still suggests that the the transfer of electrons is intimately involved in the bond. So in her third interview she explains that ionic bonding "involves the transfer of electrons, the metals usually lose electrons and become cations, and they're accepted normally by non-metals, which which become negatively charged to become anions and the positive and the negative atoms are attracted to one another which is what the ionic bond is" (N3.A045). In a concept map prepared as a revision exercise she wrote that,

> "Ionic bonding is associated with transfer of electrons, this type of bonding occurs between non-metals and metals, the metal loses electrons (hence becoming a cation $^{n+}$) to the non-metal which acepts [sic] them to form an anion of $^{n-}$ charge. The idea is to attain full outer shells (noble gas config.) - more stable, the two oppositely charged species then attract to form an ionic compound e.g. Na^+Cl^-." ...
> (Concept map on chemical bonding, June 1993.)

Although appreciating the electrostatic nature of the bond ("the positive and the negative [ions] are attracted to one another which is what the ionic bond is"), Noor still feels she needs to start her explanation from conjectured discrete atoms, and explains the rationale in terms of the FULL SHELLS EXPLANATORY PRINCIPLE ("the idea is to attain full outer shells"), rather than the electrostatic forces that would operate were her conjectured atoms to interact.

For Paminder, at the same stage of her course, electrostatic factors were even less significant. At the end of her first year, after being taught about bonding at A level, she wrote in a revision exercise that "ionic bonding *is the complete transfer of electrons* from one atom to another - it involves ION FORMATION" (concept map on chemical bonding, June 1993). In an interview at this time Paminder explained her conception of the difference between covalent and ionic bonds was that "covalent bonding was sharing electrons, [ionic] *is the transfer of electrons*" (P3.A451).

Umar's explanation of ionic bonding, given in an interview near the end of the first year of his course, did include attraction between the charged ions. However he also thought it appropriate to refer to electron transfer: "sodium has *lost* an electron to the chlorine, and the sodium *lost* one electron to form a cation and the chorine's *gained* an electron to form an anion, and like the positive and negative charges between them attract to form these bonds" (U3.A403). In a concept map prepared as a revision exercise at the end of his first year Umar described the ionic bond as where "the atoms *achieve noble gas configuration to form anions or cations* which attract each other", and described the cations and anions as "+ve ions which *have lost* e^- to achieve noble gas configurations" and "-ve ions which *have gained* e^- to have noble gas configuration" (concept map on Chemical Bonding, June 1993). The attraction between the ions seems to be considered a by-product of the bond, which is construed in terms of the FULL SHELLS EXPLANATORY PRINCIPLE.

When Umar was interviewed near the end of his course, he still used the FULL SHELLS EXPLANATORY PRINCIPLE, and the notion of electron transfer, to describe the ionic bond, so that "the sodium forms a sodium plus ion 'cause it *donates* an electron to chloride ion, chloride atom to form a chloride ion so they both achieve noble gas configuration" (U4.A346).

§A35.2.4: Incidental data.

In chapter 11 (§11.4.2) it is suggested that incidental data collected from other learners suggests that the definition of the ionic bond in terms of electron transfer is not restricted to the students interviewed for the research. The following definitions and explanations of ionic bonding are taken from exercises set as part of induction into the A level chemistry course,

- "Ionic bonding is where electrons are passed from the outer shell of one atom to the outer shell of another. The atoms then become ionised and attract to each other" (induction exercise, September 1991).
- "Ionic bonding is when 2 chemical atoms (usually a metal and nonmetal) bond by transferring electrons. ... Sodium Chloride is ionicly [sic] bonded, Sodium loses an electron to Chlorine" (induction exercise, September 1991).
- "ionic bond is a bond where electrons are lost or gained" (induction exercise, September 1993).
- "Ionic bonding is the transfer of electrons from one atom to another" (induction exercise, September 1991).
- "Ionic bond - This is when an atom loses or gaines [sic] an electron to form an outer shell to bond" (induction exercise, September 1993).
- "Ionic bond - when an atom gives an electron to another atom to create a full outer shell" (induction exercise, September 1994).
- "Sodium has a valency of 1 and require to lose one electron in order to stablize. Chlorine has a valency of 1 it needs to gain one electron. The chloride and the sodium therefore form an ionic bond where sodium donates an electron and chlorine receives" (induction exercise, September 1994).
- "IONIC; the donation of electrons. e.g. If one atom has one electron in its outer shell, and another has 7, the first atom may donate an electron to the second in order for both of them to become stable" (induction exercise, September 1995).
- "The sodium & chlorine form an ionic bond to become sodium chloride. To become stable a sodium atom must lose an electron & a chlorine atom must gain an electron; giving the ions Na^+ and Cl^-. These ions joined together because the sodium ion 'donates'

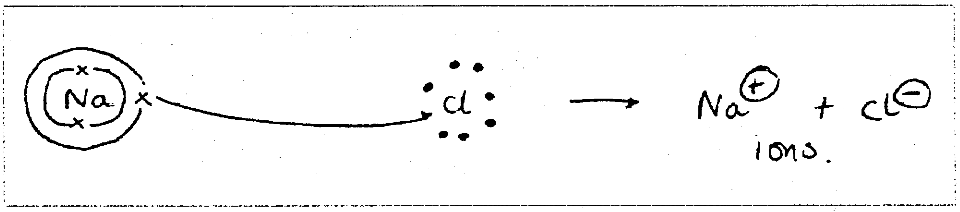
an atom to the Chlorine ion; thus forming an ionic bond" (induction exercise, September 1994).

§A35.2.5: Incidental data.

In a mock A level examination (March 1994) question some of the students' explanations of the bonding in sodium chloride demonstrated the same features,

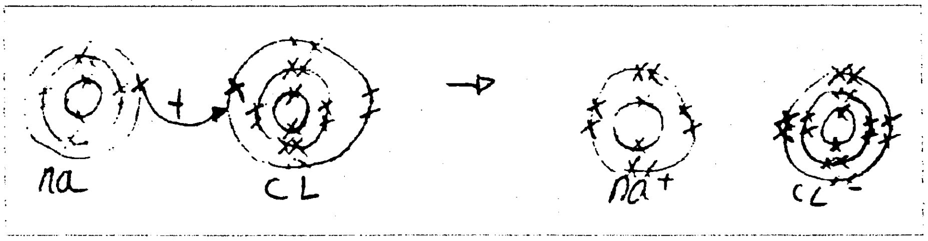
- "NaCl: bonding is ionic with the Na atom donating one electron to the Cl atom."
- "Sodium chloride, has ionic bonding, in which electrons are transferred from, one atom to another."
- "The bonding present in NaCl is electrovalent since Na loses an electron an [sic] Cl gains an electron."
- "The compound is ionic in its bonding. There is a complete transfer of electrons thus forming Na^+ & Cl^- ions."
- "Sodium Chloride consists of Ionic bonding. Sodium looses [sic] one of its outer electron to the Chlorine and the Chlorine atom gains this electron. Both achieve an stable noble gas configuration."
- "Bonding in sodium chloride is an ionic bond which is formed when sodium gives up 1 electron in the outershell and the chlorine atom is available to accept it to fill up its outershell."

The same concerns were represented graphically by some candidates,



"Sodium chloride - ionic bonding in this solid:-
As the Sodium has an electron in it's [sic] outer shell it can donate this electron to the chloride to form a stable ion with a full outer shell."

(Mock examination response, March 1994.)



"Sodium loses electron becoming positive chloride gains an electron becoming negative"

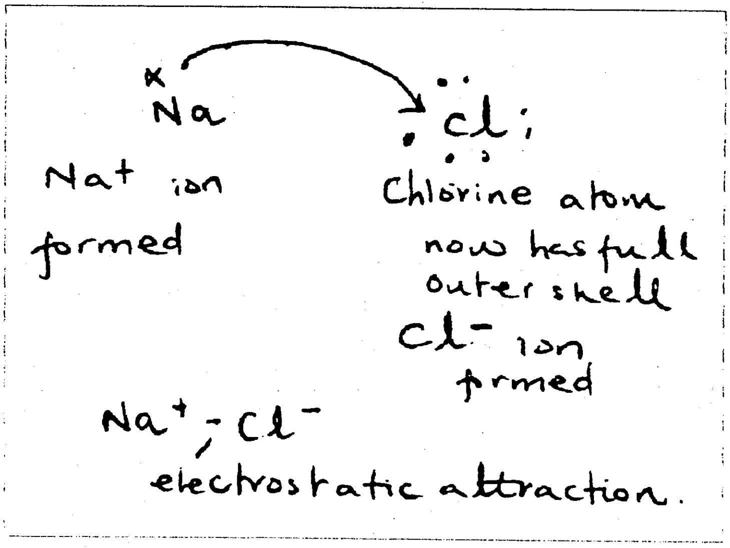
(Mock examination response, March 1994.)

§A35.2.6: Incidental data.

Some responses that mentioned the electrostatic forces, still focused on electron transfer,

- "Bonding is ionic involving a total transfer of electrons from one atom to the other and then an electrostatic attraction between the ions formed, forming the bond."
- "The bonding present in NaCl is Ionic bonding. This type of bond involves the complete transfer of electrons to form ions. The bond is an electrostatic force of attraction between 2 oppositely charged ions. Na in group 1 has an electronic Configuration of $1s^2 2s^2 2p^6 3s^1$ To get more stable it needs to lose the electron in the s orbital. Chlorine has an Electronic Configuration of $1s^2 2s^2 2p^6 3s^2 3p^5$ To become more stable it needs to attract one electron therefore it has a high electron affinity."

The following diagram, from an answer in the same mock examination, is another example that mixes the two themes of *electron transfer to give full shells*, and the *electrostatic forces*,



(Mock examination response, March 1994)

§A35.3: References to ionic molecules.

In chapter 11 (§11.4.3) it is suggested that in the present research it was found that the particular ions that were conjectured to have been involved in a specific electron transfer event were sometimes considered to be a molecule.

§A35.3.1: Annie, Brian, Jagdish, Kabul, Tajinder, Umar.

A number of the colearners explicitly referred to molecules in sodium chloride.

Annie referred to a molecule of sodium chloride, in her third interview,

> A If you get a molecule of sodium chloride, the overall charge is neutral, due to the fact that the sodium's donated an electron, and the chlorine's accepted, an electron.
> I: Do you know what the formula of a molecule of sodium chloride would be?
> A: Yeah, NaCl.
> I: And how many atoms would be present in that molecule?
> A: Two.
> A3.30

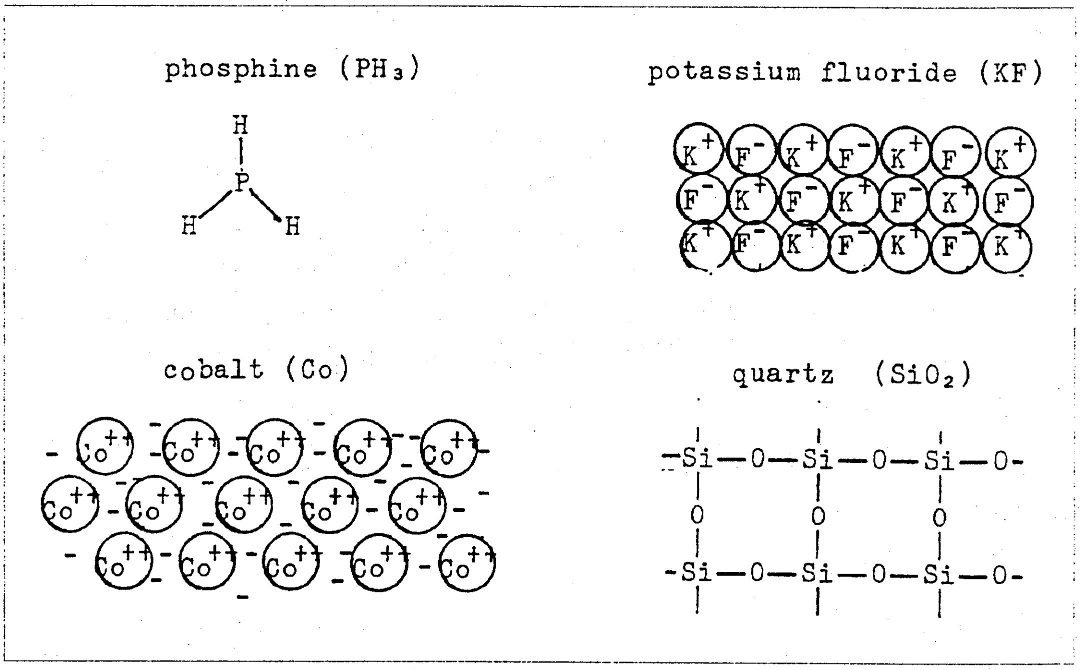
Later in the interview Annie said that she thought crystals of sodium chloride comprised of "sodium and chlorine atoms joined to form the *sodium chloride molecule*" (A3.120).

In Brian's first interview he referred to the "sodium chloride molecule" (B1.242). In his second interview Brian thought there were "numerous" molecules present in focal figure 5 (B2.30). However he considered that each ion was part of a molecule with *each* of its neighbouring counter ions, rather than just one (B2.40). (By his final interview Brian had decided that there were no molecules shown in the diagram.)

In Jagdish's first interview she describes focal figure 5 as being "a lot of sodium chloride molecules": on counting "fifteen" (J1.A157). Jagdish was able to suggest which ions may be part of the same molecule. She realised her assignment was arbitrary, and she accepted alternative nominations - as it "depends on which one you want it to be", it "just depends on which one you think looks better" (J1.A179). However, she believed that an ion cannot be in two different molecules at once (J1.A168): she thought a molecule was "two or more, atoms, joined together" (J1.A186), and she explained that,

> "if that [ion]'s joined to that one, that is the molecule. But that one can't be joined to that one, at the same time as joining to that [other] one."
> J1.A190

Kabul demonstrated some uncertainty about the application of the *molecule* concept to ionic materials. In his first interview he had *not* thought there were molecules in focal figure 5. In his second interview, he suggested otherwise, that atoms are made into molecules "in ionic and covalent bonds" (K2.A099). He referred to "intermolecular forces" in sodium chloride, but *then* denied that there were any molecules present (K2.A322).



'four substances' (diagram used in classroom exercise)

Later still in the interview Kabul was asked about a question in a class test he had taken at the end of the first term (where diagrams representing unfamiliar materials - see above - were to be matched to the expected properties). Kabul had been asked to identify the substance in the diagram that had a *giant molecular structure* (i.e. quartz), and in the test he had suggested cobalt. In the interview, he suggested that it would be "probably potassium fluoride" (K2.A452). For Kabul, a 'giant structure' meant "it is a macromolecule, ... [a] very big molecule" and 'giant *molecular* structure' meant one "in which there are strong covalent bonds existing between the atoms" (K2.A452). With this in mind, Kabul still thought that the giant molecular structure was "probably potassium chloride" (K2.A542). After some discussion, and Kabul expressing some doubt about the presences of covalent bonds and molecules (K2.A561, K2.A572), he decided that there were strong covalent bonds *between* potassium fluoride molecules (K2.A581), and he was able to identify potassium fluoride molecules on the diagram. The molecules were pairs of ions (one potassium ion, one fluoride ion), and there was a strong covalent bond "between the pairs" (K2.A585). The bond between ions in the molecules was an "ionic bond", whereas "between the molecules, then probably it would be a covalent bond" (K2.B003). Kabul concluded potassium chloride *was* a giant molecular structure (K2.B045).

In Tajinder's first interview he referred to the arrangement of ions in focal figure 5 as "a group of molecules", and he considered a pair of ions as "a molecule" (T1.A446). Moreover, he was confident in which pairs of ions make up a molecule,

> I: Are you sure it's *that* sodium and *that* chlorine that's a molecule,
> T: Yeah.
> T1.A446

Later in his first term, Tajinder undertook Kelly's repertory test, and one of the constructs elicited was 'molecule'. One element construed as being on the emergent pole of the construct represented a NaCl lattice, and Tajinder *also* construed this element at the emergent pole of the construct 'ionic bonding' (November 1992). So at the beginning of his course Tajinder thought that there were molecules in ionic materials.

In Umar's first interview for the research he referred to focal figure 5 representing a "sodium chlorine molecule" (U1.A335). By the end of his course Umar was unsure whether it was appropriate to talk of molecules in this context,

> "they're not any individual molecules, they're part of a complete lattice, 'cause it's, it's a giant lattice, you couldn't, ... you couldn't say that there's specific molecules, but, they belong, you could say there's individual molecules forming a giant lattice, but • • • (yeah) • • I'm not really sure about that."
> U4.A455

Umar still thought that an ion pair was a molecule, so when an adjacent sodium ion and chloride ion were indicated, he said "that is a sodium chloride molecule" but when asked whether each ion was apart of six distinct molecules he was "not sure" (U4.A455).

§A35.3.2: Incidental data.

In chapter 11 (§11.4.3) it is suggested that 'incidental' data collected from other learners shows that the notion of ionic molecules is not restricted to the colearners interviewed for this research. For example, consider the following typology of chemical bonds from a student setting out in A level study,

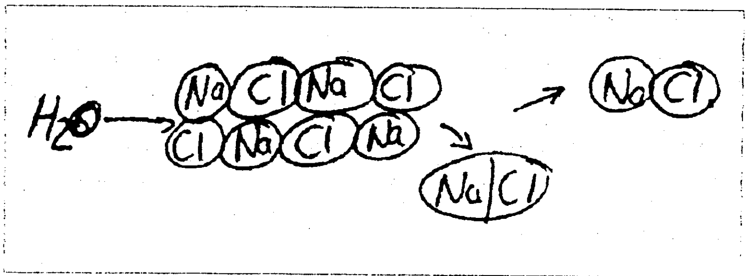
> "Chemical bonding comes in two forms :- Covalent Bonding ... Ionic Bonding ... Both forms of bonding create molecules and even substances."
> (Induction exercise, September 1993.)

Students may then see the dissolving of ionic materials in terms of the solvation of molecules rather than ions,

> "The water surrounds the sodium chloride. The water molecules attract the *sodium chloride molecules*, thus causing the sodium chloride to break up, The water molecules, which are continually moving, move *the sodium chloride molecules* around the water until the sodium chloride is equally dispersed in the water + has dissolved."
> (Induction exercise, September 1994.)

Of course the term 'molecule' could be meant generically in the statement given above, and could conceivably be intended to include 'ions'. However, in the following example the student has illustrated the process of dissolving, thus making it clear that the sodium chloride molecules referred to are ion-pairs,

> [Sodium chloride dissolves in water] "because the water breaks up the large salt crystall [sic] into tiny *molecules of NaCl*, I don't think that any atomic changes go on in this process."



(Induction exercise, September 1994.)

§A35.3.3: Incidental data.

References to ionic molecules were also found in work undertaken by students *during* their A level course. For example, in the following extract the ion-pairs conjectured to have been involved in electron transfer are described as molecules,

> "Sodium chloride molecules are bonded together by strong ionic bonds which sees the transfer of one electron from the sodium atom to the chlorine atom, this leaves a *molecule of sodium chloride* consisting of a (Na^+) Sodium ion and a Chloride ion (Cl^-)."
> (Mock examination response, March 1994.)

And another answer distinguished between the intra- and inter-molecular forces,

> "Sodium Chloride is made up of ionic bonds between single Na-Cl atoms but van der waals bonding between adjacent *molecules*"
> (Mock examination response, March 1994.)

The same point was made in an assessment response by a first year student,

> "The bonding present between NaCl is ionic but *from molecule to molecule* weak V.D.W forces"
> (First year assessment response, February, 1996.)

Appendix 36.

Evidence of octet thinking: the valency conjecture.

§A36.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.5.

§A36.1: Electrovalency as the determinant of the number of ionic bonds formed: the valency conjecture.

In chapter 11 (§11.5) it is suggested that a number of the colearners in the study demonstrated the tendency to think that ionic bonds can only occur where there has been electron transfer, then the number of ionic bonds that an atom may form is determined by the number of electrons it will donate or accept in reaching an octet state, i.e. by the electrovalency.

§A36.1.1: Carol.

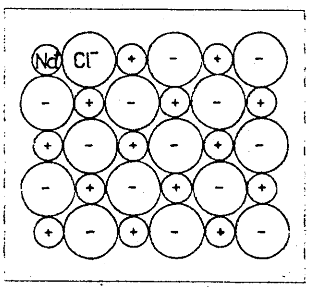
In Carol's first interview she demonstrated some confusion over the number of bonds an ion could be said to have in a lattice. She supposed that there was an ionic bond "where it comes in contact with an, another, atom ... I suppose on the bits where the circles are touching, perhaps" (C1.256). Yet she was not sure whether each ion could only have one bond (C1.257), or whether the atom could form a greater number that was somehow related to electronic structure,

> "as many [ionic bonds] as it wants, *as long as it's got electrons to cover how many it does want*. Because all the rest just carry on orbiting."
> C1.262

In the second interview Carol continued to be uncertain about this. She first suggested that in sodium chloride "each one does one bond" (C2.147). However as the ions had a "co-ordination number of six" (C2.193) Carol thought "you *could say* it forms six" (C2.199). Carol appeared to be operating from a mixture of 'octet' and electrostatic thinking, which would predict different numbers of bonds. This was demonstrated when she asked - from the perspective of the FULL SHELL EXPLANATORY PRINCIPLE - how a sodium ion could have six bonds, and then suggested her own answer in terms of the CURRICULUM SCIENCE perspective,

> "how come, if you say that, like it's bonded to six others, how come it isn't Na^{+6} because it, because you're kind of saying, that it loses an electron every time it bonds ... it should be Na^6 really ... Mind you ... it only needs to lose one, doesn't it, to become positive."
> C2.233-5.

By her final interview Carol seemed to have accepted the latter view, and thought that the ions in NaCl formed "six" bonds (C3.658).



focal figure 5

§A36.1.2: Kabul.

In Kabul's first interview he suggested that a sodium ion in focal figure 5 has "four" ionic bonds, but then he suggested "if it was a three-dimensional figure it would have been much better" (K1.A154) as he would then be able to tell from the diagram that,

> "this sodium is attracted to chlorine over there, this one is attracted over there, this one will be over here, this one, would be attracted to that one. Like that. Because sodium has got only one electron. It can not, it can not give to four ... four chlorine atoms its electron, it can give to only one of the chlorine atoms."
> K1.A154

He thought that in the actual structure each sodium ion formed "one bond" (K1.A154). Kabul was prepared to identify which chloride ion he thought was bonded to a particular sodium ion. He did this by developing a pattern based on the assumption that the two ions specifically labelled as 'Na^+' and 'Cl^-' (rather than just '+' and '-') were meant to be signified as bonded (K1.A277). However, Kabul seemed to demonstrate a metacognitive awareness that this was arbitrary.

K: ... in the diagram over here you have shown - sodium and chlorine, it shows these will bond like this, so over here the same thing, this thing will bond with that thing.
I: Mm. So do you think this sodium-plus here, where I've actually written 'Na',
K: yeah
I: is any different to any of the other sodiums?
K: No.
I: And this 'Cl^-' is that different to any of the others.
K: No.
I: So why haven't I written it on all of them?
K: Just to, just to same time.
I: Right, so if I'd chosen to write N-A-plus in that sodium,
K: yeah
I: but C-L-minus in this ion > here >
K: < yeah <
I: instead,
K: Yeah, then probably I would change my decision.
I: You'd change your decision.
K: Yeah.
I: So I can actually sort out where the bonds are going to be by choosing which ions I label.
K: Yeah.
I: Oh, that's quite nice to know. Right,
K: I don't think so that's right, but, it's my just thinking that it will be like that.
K1.A277

Despite this recognition, Kabul still thought his assignments applied (K1.A277). Later Kabul accepted that a sodium ion could be bonded to *any one* of the surrounding chloride ions, but *only* "one of them" (K1.A328), and the bond was fixed to a particular counter ion (K1.A333). It seemed that he was distinguishing the actual structure where it would be clear which counter ions were bonded, and the limited two dimensional representation where an arbitrary assignment could be made. When the diagram was revisited later in the interview Kabul at first suggested that a sodium ion "has got four nearest neighbours", although "it will be attracted to only one of them" (K1.B217). However, again he apparently meant the "four nearest neighbours" to be referring to the diagram, as he thought that in a three dimensional representation the ion would have "only one" nearest neighbour (K1.B217).

By his second interview Kabul had read up about the structure in a text book, but the CURRICULUM SCIENCE perspective appeared to confuse him. He explained that he thought there would be a force between a particular sodium ion in sodium chloride and only one chloride ion as "it's just bonded to one" (K2.A380). Similarly, each chloride ion would be attached to one sodium ion - the one that was attached to it (K2.A387). Kabul thought this although he had seen "in the text book that they are joined to something else, but I don't know the explanation" (K2.393). This alternative approach would explain the integrity of the structure as "it forms a crystal" and the sodium ions are "not only held to one chloride ion. They're held to many" (K2.A398), "probably a specific number" (K2.A404). But Kabul still thought that it was when an electron was transferred between two atoms that "a bond exists between them" (K2.A417). He explained that a "sodium atom loses one electron. [And the chlorine atom] gains one electron", so "it should just form one bond. But as I told you, I saw in a text book, it forms four bonds" (K2.A421).

After the second interview, when we were packing away, Kabul made an interesting comment which somewhat clarified his thinking about the ionic bond. As we had agreed to another interview two days later to discuss some other diagrams, I started this third interview by asking Kabul to repeat his comments. He suggested that the reason why an ion might only be able to form one bond was that the charge would be 'cancelled' when the ion bonded,

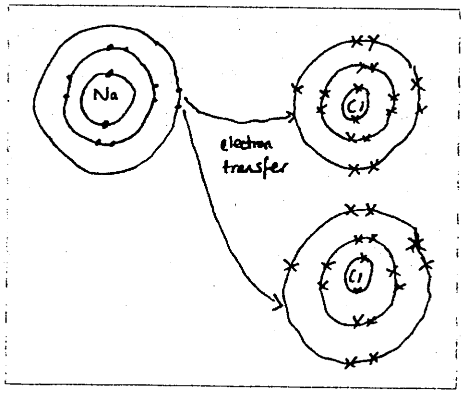
> "Well, I was just saying, because sodium has got erm, an overall charge of plus one, it will just attract one chloride ion. So in the crystal, in a crystal of sodium chloride, one sodium ion should be attached to only one chlorine, chloride ion, and not more than that. ... Because a positive charge attracts a negative charge. Once it has attracted, the overall effect is cancelled out."
> K3.A033

So in calcium chloride the calcium ion had a charge of "plus two" and could attract "two" chloride ions, whilst "two chloride ions will attract one calcium ion" (K3.A044). One chloride ion could "probably" attract "half" a calcium ion, although this "is not possible" (K3.A044). Kabul's belief about the way a charge could only attract a charge of equal magnitude would appear to be similar to the 'conservation of force' notion (discussed in chapter 10, §10.5).

Later in the interview Kabul was asked once more about sodium chloride. He was still struggling with the relative merits of the valency conjecture (which made sense to him, but did not explain the integrity of the crystal lattice) and the textbook model which required more bonds than he could explain. Kabul then thought that in a crystal of sodium chloride there would be "one" chloride ion around each sodium ion, at least "theoretically one, but - I've just seen some textbooks that they're more than one" (K3.A141). These chloride ions "seem to be [at equal distance from the sodium ion] in the text book" (K3.A141). If the sodium was forming "one bond with each", then it would be forming "four [bonds], which I don't think it's possible" (K3.A148). Kabul thought "the situation is *one sodium ion forms a bond with one chloride ion*", although this was "also not possible, otherwise ... in a crystal, sodium chloride, it will just fall apart" which "doesn't happen" (K3.A153). Kabul had not "got any explanation to that" (K3.A153).

§A36.1.3: Lovesh.

In Lovesh's first interview for the research, he demonstrated that he also operated with the valency conjecture. So in sodium chloride the sodium ion was "bonded to chlorine ... it'd be two, because sodium donates two electrons to two chlorine atoms" (L1.A314). In his case he was taking the electrovalency of sodium as 2, as in his diagram of ionic bonding.



detail from Lovesh's diagram of ionic bonding, November 1992

§A36.1.4: Noor.

In Noor's first interview for the research she started to apply the valency conjecture, but then changes her mind. She says that in sodium chloride a chloride ion would only be bonded to one sodium ion,

> "because it's only receiving one electron, from the sodium. So it's only going to bond with one sodium. But they'll bond with others as well to form the lattice. ... I'm contradicting myself there"
> N1.A322

§A36.1.5: Paminder.

In Paminder's first interview for the research she demonstrated the valency conjecture when she demanded an explanation for the arrangement of ions shown in focal figure 5. Paminder stated that one of the sodium ions would be bonded to "one" chloride ion, but asked "then how how come it's got four?" (P1.A307). She wanted to know,

> "how is it possible, if this is like saying ... 'Na's in the middle, and you've got four 'Cl's there, but how can you have that when, *there's only one electron in the sodium, to give to one chlorine*, so how are these three, how are they attached to that?"
> P1.A307

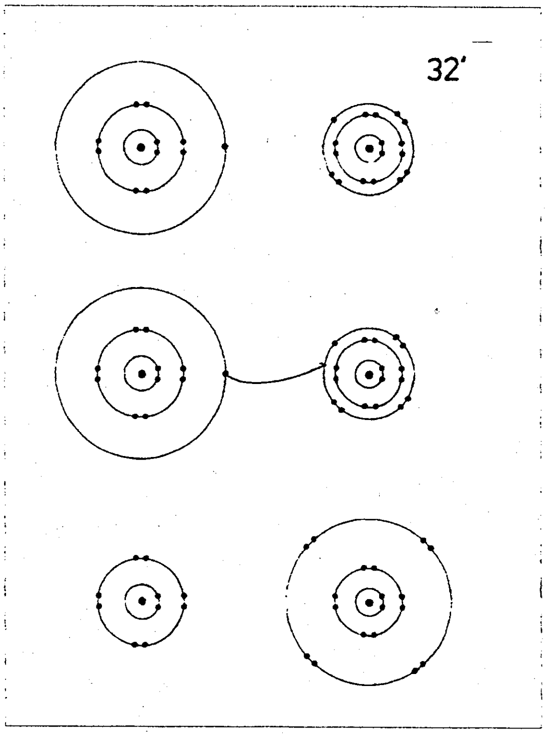
Paminder thought the diagram was incorrect,

> "the way it looks, when you look at it initially, when you look at it you think, like what I just told you, you think that's not possible. So when you first look at it you think the diagram's wrong."
> P1.A307

By the end of her first year Paminder seemed to react less strongly to the diagram, but she still thought the diagram was inaccurate, because it did not seem to fit her valency conjecture. Sodium had formed "four [bonds] *by the looks of it*", but "it just appears [that way] on the diagram but I don't think it actually has" (P3.A463).

§A36.1.6: Tajinder.

In his first interview Tajinder assigned ions to molecules in focal figure 5. He explained that "I think it is only bonded to one, one chlorine is only bonded to one sodium, because a sodium atom can only lose one electron, so, therefore ... it's not like carbon where ... it can gain four bonds, it can only gain one bond" (T1.A446).



focal figure 32'

Later in the interview, Tajinder again used the valency conjecture, when asked about the ion-pair shown in focal figure 32,

I: And would these, either of these ions be able to form a bond with any other ions, or would it just be the one they've transferred an electron with?
T: It would only be the one it's transferred to, because *it has no other outer electrons to form another bond with*.
I: So it will only form one bond?
T: Well, in this case, yeah, only one.
T1.C065

Appendix 37.

Evidence of octet thinking: learners' bonding dichotomies.

§A37.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

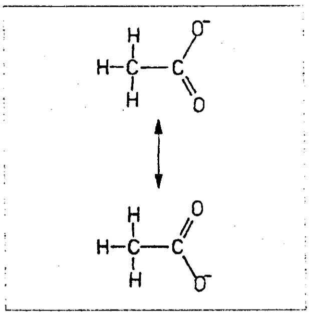
It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, subsection §11.6.1.

§A37.1: Learner's dichotomies.

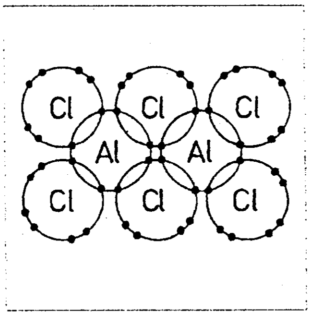
In chapter 11 (§11.6.1) it is suggested that typically learners commenced A level with distinct models of covalent and ionic bonding, and criteria to distinguish the two cases.

§A37.1.1: Annie, Debra, Jagdish, Kabul, Lovesh, Tajinder.

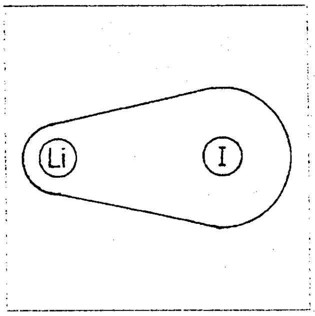
Annie defined a covalent bond as "a bond that is formed between non-metals" (A1.71), so that "covalent are non-metallic bonds, so when you get a single bond from ... carbon to hydrogen that's, they're both non-metals, so that would count as a covalent bond" (A1.744).



focal figure 13



focal figure 15

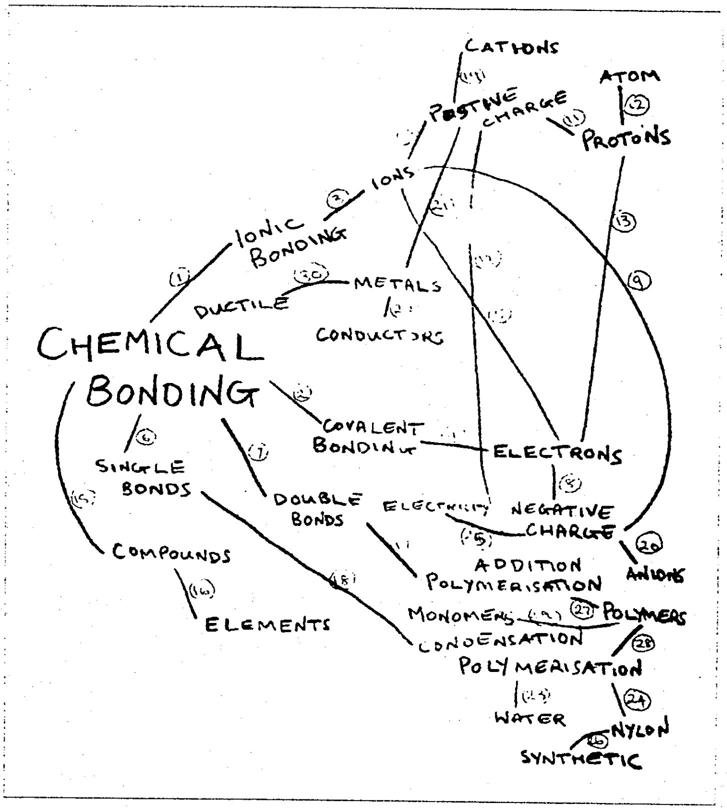


focal figure 8

So for Annie in the carbon-oxygen double bond represented in figure 13 (the ethanoate ion) "that's covalent in that case because it's two non-metals joining" (A1.540). Conversely, Annie categorised the bonding in focal figure 15 as "ionic" (A1.574) "because it's a metal and a non-metal combining" (A1.578). In her third interview however Annie offered an alternative distinction, that in covalent bonding "they share electrons" and in ionic bonding "one of them donates, an electron" (A3.412-4). In the final interview Annie repeated this distinction, that an ionic bond "involves, one of the atoms donating all of the electrons, to the other one ... so you've got, sort of complete transfer of electrons. Rather than sharing" (A4.14) However, Annie continued to apply her previous criterion, so figure 8 would probably be "ionic" (A4.284) because "you've got a metal and a non-metal" (A4.286). Annie refers to the "***polarisation*** within the, ***the molecule***. 'Cause, 'cause one is, sort of attracting more more than the, more so than the other" (A4.288), but still classes the species as ionic (A4.292), because "of just the, the metals [sic] that you've got there. Of a metal and a non-metal. That's the way that they normally combine" (A4.302).

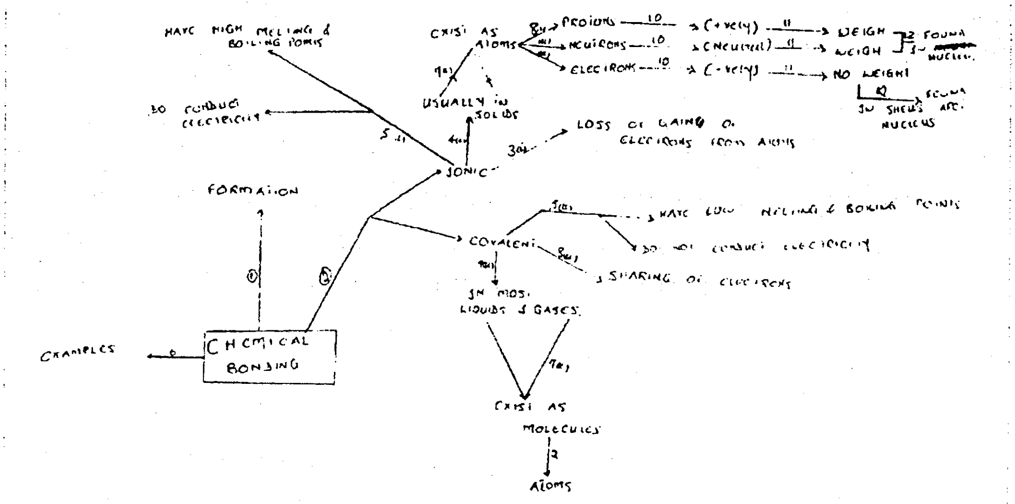
In Debra's first interview she defined the covalent bond as "sharing of a pair of electrons" (D1.670) and an ionic bond as "when one electron's lost from an atom, and given to another atom" (D1.672). Debra thought the criterion that distinguished whether a bond was ionic or covalent was "whether ... both were metals or ... one was a metal and one was a non-metal" (D1.656).

When Jagdish was asked to produce a concept map of 'chemical bonding' as an introductory exercise at the start of her A level course, she included four categories of bonding: 'ionic bonding', 'covalent bonding', 'single bonds' and 'double bonds'.



Jagdish's concept map on Chemical Bonding, September 1992

Kabul included two "types" of chemical bonding, 'ionic' and 'covalent', in a concept map (below) drawn as an introductory exercise at the start of the course.



Kabul's concept map on 'chemical bonding', September, 1992

In an interview near the *end* of Lovesh's course he defined chemical bonding as being either covalent or ionic, so that "a chemical bond is an attraction between two atoms whether they're *either sharing electrons or one's donated an electron to another* so you get a positive and a negative ion being attracted together" (L4.A029).

Similarly, in Tajinder's first interview he was asked what bonding was, and he explained that "you can have two types of bonding, electrovalent, covalent ... ionic or covalent" (T1.A102).

§A37.1.2: Incidental data.

In chapter 11 (§11.6.1) it is reported that the interview study suggests that students were only likely to have any detailed knowledge of two types of bonding when they enrolled on an A level course, and this is supported by evidence collected from students setting out on A level chemistry,

- "1. Ionic Bonding is one form of chemical Bonding. 2. Covalent Bonding is the other form of chemical Bonding. 3. Bonding involves either the transfer or sharing of electrons" (Induction exercise, September 1991).
- "There are two types of bonding. IONIC When atoms try to get a full outer shell when bonding. COVALENT When atoms share pairs of electrons" (Induction exercise, September 1991).
- "chemical bonding comes in two forms:- Covalent Bonding - joining of 2 or more shells to form complete outer shells. Ionic Bonding-Transfer of electrons from outer shells" (Induction exercise, September 1993).
- "bonding is when 2 atoms chemically combine to become a molecule of sorts. The 2 types of bonding are IONIC (donating electrons) and COVALENT (sharing electrons). It is done in order to try to achieve a stable structure i.e. 8 electrons in the outer shell of the atom" (Induction exercise, September 1995).

§A37.1.3: Paminder.

Paminder also used the dichotomy covalent-ionic near the beginning of her course, but she did not seem to have *explicit* criteria (such as whether the elements involved were metal or non-metals) for determining bond type. Although Paminder would assign bonds to one of the two categories, it was not possible to elicit her criteria, although *she* seemed to feel the classifications were not arbitrary. She was asked about the kind of bonding in hydrogen fluoride in an interview near the beginning of her second term of A level work. She was unsure whether the bonding was ionic or covalent. At the beginning of the following exchange Paminder changes her mind about the type of bonding in hydrogen fluoride.

I: What kind of bonding would you expect hydrogen fluoride to have?
• [pause, c.1s]
P: Erm, ionic. I think, hold on, hydrogen is plus one, minus one,
• • • • • • • •
P: hold on one minute.
• • • • • • •
P: Yeah, ionic I think, yeah, if it, hold on. Fluorine is in group seven, so it has valency of minus one, and hydrogen has a valency of plus one. Yeah?
I: Uh hm.
• • • • •
P: (So it's) • covalent then, 'cause it can't be ionic then, can it?
I: Can it not be ionic?
P: {laughs}
P2.A106

It is not clear here why Paminder decided the bonding could not be ionic in this case, so she is asked how she decides between the two classes of bond she has suggested,

I: How would you decide whether something's covalent or ionic?
...
P: Like, if, if I had say one element from group 1, or something, then I had, like say for oxygen for example, it's got six electrons in its outer shell, outermost shell, and so to get that shell filled up needs two more electrons, right, to make eight, so if it has two hydrogen atoms you can make H_2O, and then the outer shell of the hydrogen atom will be full, in both hydrogen atoms, and the oxygen outer shell will be like done as well, but that would be covalent bonding.
I: Uh hm?
P: You know, they'll be sharing it,
I: Yeah.
P: but if it's ionic it's like the transfer, like one will like lose or gain an electron to become stable.
P2.A125

At this point Paminder has explained that she conceptualises the two types of bond as sharing and transfer of electrons, and she has explained the bond in water according to the FULL SHELLS EXPLANATORY PRINCIPLE. However this principle would be equally satisfied by an ionic bond between the hydrogen and oxygen, so the question was put again,

I: So how do you decide whether it's going to be ionic or covalent, do you just happen to know some of them, or is there a way of deciding?
P: There is a way of deciding I told you, 'cause like, suppose you have like seven electrons in the outer shell, yeah?
I: Mm.
P: And like to need, to get it filled up, you need one, okay? And another, another atom might just have one electron in its outermost shell, it's easier for that one to like loose that outermost electron than to gain seven, isn't it?
I: Yeah?
P: So that one can lose, that's one electron to the one with seven electrons in its outer shell, so now they've both got full outer shells.
I: So that would be ionic?
P: Yeah.
P2. A136

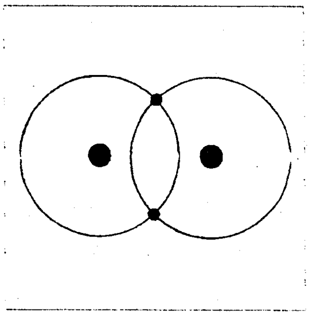
Paminder seems to think she has explained how she distinguishes the two cases, ("I told you"), but her subsequent attempt at explanation only describes why an ionic bond would form. In addition, this example of ionic bonding - a group 1 element and a group 7 element - includes the case of hydrogen fluoride that she has just claimed *can not* be ionic. The question was now put in terms of a specific example,

I: But the example you gave about erm water, > hydrogen and oxygen, >
P: < is covalent. <
I: that's covalent.
P: Yeah.
I: So why is that not ionic?
P: Because it is not actually the transfer of electron, it's the sharing of it, they've like both got control over - that electron.
I: Mm. So how did you decide that was going to be covalent rather than ionic, though?
P: Because, erm, it's like,
• •
P: hard to decide.
P2.A146

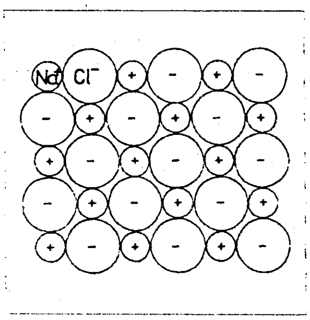
It would appear that Paminder did not have any specific explicit criterion for deciding *whether* an unfamiliar compound was likely to have ionic or covalent bonding. Despite this, it may be seen that she remains confident in her assumption that the bond would be *either* covalent or ionic.

§A37.1.4: Carol.

Carol also used the covalent-ionic dichotomy to classify bonds, but whereas in the learners discussed above these two categories are discussed as if of equal standing, Carol construed ionic bonds to be in some way a lesser category. Indeed in order to interpret her comments coherently it became necessary to conjecture that Carol used the word 'bond' in two distinct ways, where bond(1) is a covalent - and one might almost say a 'proper' - bond to her mind, whilst bond(2) is just an attractive force.



focal figure 2



focal figure 5

In Carol's first interview she recognised covalent bonds in focal figure 2 where there were electrons shown at points of overlap, "where the circles overlapped there was electron, ... on the kind of the corners" (C1.288). Where there was no overlap shown, Carol did not perceive any bond, ***at least not a covalent bond.*** So between molecules of hydrogen fluoride "there's, no overlap is there, so I don't think there is a covalent bond" (C2.420).

Whereas Carol perceived the covalent bond as sharing of electrons, which would be represented by overlap of atoms, the ionic bond then appeared to be construed as a significantly different sort of entity. In the first interview Carol identified figure 5 as showing an "ionic compound" (C1.248), but,

> "there's no bonds in the same way as we've seen them before. There's no circles that are crossing over, each other. So if that's what bond means, then no there isn't any bonds, but, there's got to be something holding them together and [it] looks like erm an attractive force or something. 'Cause sodium's positive and chlorine's negative so they're attract[ing] each other."
> C1.250

This would be an "ionic bond" (C1.252). Similarly, in her second interview Carol reported that in focal figure 5, "there's no overlap, so you could say there isn't really any bonds, but there is, there is because there's an attractive force between the sodium and the chloride ions, but it's not a covalent bond, it's an ionic bond" (C2.141). There is a sense here in which 'bond' seems to have two meanings 'bond$_1$' is a covalent bond, whereas 'bond$_2$' is just an attractive force: a bond$_{(1)}$ requires "circles that are crossing over, each other", "overlap". In focal figure 5, "there's no overlap, so you could say there isn't really any [bond$_1$s], but ... there [are bond$_2$s] because there's an attractive force between the sodium and the chloride ions, but it's not a [bond$_1$, i.e. a] covalent bond, it's an [example of a bond$_2$, an] ionic bond."

Even in her final interview Carol seems to retain the distinction between the two meanings of bond. In a figure showing a potassium ion and a fluorine ion Carol reports that the electron density shown represents "the bonding, electrons" (C3.927), but these electrons are

> "not in a bond. The electrons aren't in a bond, it's, they've been transferred, so, it's more of an attractive bond."
> C3.929

The apparent contradiction disappears if the two meanings of bond are admitted: "the electrons aren't in a [bond$_1$], it's, they've been transferred, so, it's more of an attractive [bond$_2$]." Carol agreed that when discussing ionic bonding she would use slightly different language "because, it's more signs you talk about isn't it, like charges" (C3.933).

§A37.1.5: Carol.

The tendency of learners to distinguish between chemical bonds and just forces is discussed in chapter 11 (§11.7), but Carol was unusual in seeming to class ionic bonds as 'just forces'. However, if Carol did not tend to ascribe ionic bonds the same full bond status as covalent bonds, she still gave ionic bonds a higher status than other forms of bonding, such as polar bonding {which was was neither covalent (C2.422) nor ionic (C2.426)}; or van der Waals' forces {which were "not to do with exchanging electrons or sharing electrons" (C3.6).}

Appendix 38.

Evidence of octet thinking: learners' dichotomisation of bonds on the covalent-ionic continuum.

§A38.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, subsections §11.6.2 and §11.6.3.

§A38.1: Learners' classifications of polar bonds.

§A38.1.1: Quorat, Tajinder, Umar, Kabul, Jagdish, Umar.

In chapter 11 (§11.6.2) it is suggested that *before* colearners had the category of polar bond available, they tended to classify polar bonds as covalent or ionic. So in the study there were the following assignments of polar bonds:

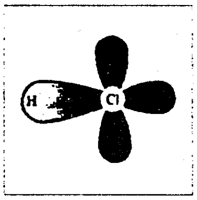
- aluminium-chlorine bond as covalent (Quorat, Q1.B009 and Q1.B479; Tajinder, T1.C134; Umar, U1.B064),
- boron-hydrogen bond as covalent (Kabul, B1.B112),
- carbon-nitrogen bond (in the cyanide ion) as "probably covalent" (Kabul, K1.A507),
- carbon-chlorine bond as covalent (Jagdish, J1.A103; Kabul, K1.A089; Tajinder, T1.A209),
- hydrogen-chlorine bond as "probably a covalent bond" (Kabul, K1.A445),
- hydrogen-fluorine bond as covalent (Tajinder, T1.C037), or

“probably” covalent (Kabul, K1.A445),

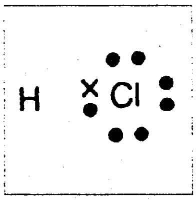
- hydrogen-fluorine bond as ionic (Umar, U1.B256),
- hydrogen-oxygen bond as covalent (Tajinder, diagram of covalent bonding, November 1992),
- nickel-carbon bond (in a complex ion) was “probably covalent” (Kabul, K1.A507),
- the bonding in sulphuric acid (triad element 443) as covalent (Kabul, construct repertory test, November 1992),
- the bonding in chloromethane (triad element 423) as covalent (Kabul, construct repertory test, November 1992).

§A38.1.2: Kabul.

In chapter 11 (§11.6.2) it is suggested that alternative figures representing hydrogen chloride molecules were construed differently by Kabul when he undertook the construct repertory test (November 1992).



triad element 552

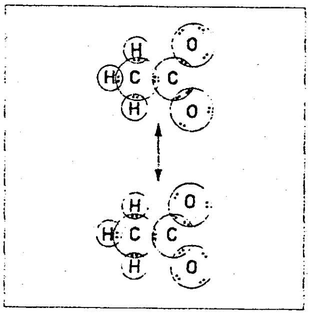


triad element 454

One (element 552) had four lobes around ‘Cl’, one of which was much larger than the others and engulfed ‘H’. The other (element 454) was a ‘dot and cross’ diagram with the electrons apparently forming an octet around ‘Cl’ so the bonding electron pair were shown much closer to ‘Cl’ than ‘H’. The former representation was construed as having *covalent bonding*, and *not* being an ionic compound, where the other representation of the same molecule was construed as being an *ionic* compound, and *not* having covalent bonding.

§A38.1.3: Kabul.

In the interviews the assignment of a bond as covalent or ionic was sometimes tested by asking the colearner to then compare bonds. So for example in Kabul’s first interview he had described the bonding in hydrogen (focal figure 2) as covalent (K1.A089), and then went on to also class the bonding in carbon tetrachloride (tetrachloromethane, focal figure 3) as “covalent bonding”. He agreed that he was therefore saying that tetrachloromethane had very similar bonding to hydrogen, and that there was the same type of bond in both (K1.A101). Kabul thought that the oxygen molecule (focal figure 4) also had “covalent bonding”, and he affirmed that the bonding was the same in the focal figures 2, 3 and 4. After discussing focal figure 5, which he had identified as ionic, Kabul repeated that the bonding in focal figure 3 was "covalent" (K1.A361), and again affirmed that the bonding was the same as in focal figure 2 (K1.A362). He confirmed that there was no real difference between the bonding in focal figures 2, 3 and 4 (K1.A367). Later in the interview Kabul again reiterated that the bonds in focal figure 3 were "covalent bonds", and not different in any way to the bonds in focal figure 2 (K1.B207), or the covalent bonds in focal figure 4 (K1.B212).



focal figure 25

Focal figure 25 represented the ethanoate ion (showing the two canonical forms). Kabul thought there was "covalent bond[ing]" in the diagram, and he counted "six covalent bonds" in each part of the diagram (K1.A479). When he was asked whether these bonds were the same he seemed to have difficulty making sense of the question,

I: Do you think there's any bonds represented in that diagram?
K: Yeah, there is covalent bond.
I: Covalent bonds. How many covalent bonds in each part of the diagram?
• • • [pause, c.3s]
K: Six covalent bonds.
I: Six covalent bonds. Are all those covalent bonds the same, do you think?
• •
K: Sorry?
I: Are all those covalent bonds the same?
K: Yeah.
I: Yeah? No real difference between them?
K: Yeah, they are covalent bonds.
I: They're all covalent bonds.
K: Yeah.
I: All covalent bonds are the same?
K: Yeah.
K1.A479

Kabul did not seem to understand how covalent bonds *could* be different - so not only did the question have to be repeated, but Kabul seemed to feel that restating that *the bonds were covalent* was equivalent to stating that there was not any real difference between them. He affirmed that all covalent bonds were, for him, the same.

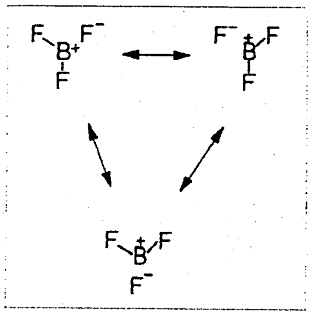
§A38.1.4: The colearners.

In chapter 11 (§11.6.2) it is suggested that it was found that there was a strong tendency for learners to often ignore the category of polar bond, and to continue to divide bonds into *covalent* and *ionic*. There are many examples in the data collected of learners who had been taught about electronegativity and polar bonding, labelling a bond as *covalent* or *ionic*, when from the CURRICULUM SCIENCE perspective it would be appropriate to use the category of *polar*:

- aluminium-chlorine bond as ionic (Annie, A1.571; Brian, B1.590),
- aluminium-chlorine bond as "covalent" (Brian, B2.166; Carol, C1.810; Debra, D1.754; Kabul, K4.B399, K4.B467 and K6.B121, Quorat, Q3.B038 and Q3.B069; Tajinder, T9.B390, T9.B461 and T10.A505; Umar, U4.B308),
- boron-fluorine bonds as "ionic bonds" (Carol, C1.792),
- boron-fluorine bonds as "covalent" (Kabul, K4.B352),
- calcium-chlorine bonds as covalent (Tajinder, T2.A380)
- carbon-chlorine bond as covalent (Annie, A1.222; Brian, B1.166 and B3.44; Debra, D1.118 and D2.101; Edward, E1.302; Jagdish, J3.B088; Kabul, K6.A308; Lovesh, L3.A300, L3.A520, L4.A222, and L4.A333; Noor, N3.A370; Paminder, P3.A336; Umar, U4.A238),
- carbon-chlorine bond as ionic (Umar, U2.B014),
- carbon-oxygen bond as covalent (Carol, C1.645-7; Kabul, K2.B054, Quorat, Q3.B141; Tajinder, T10.A308)),
- hydrogen-chlorine bond as ionic (Kabul, K2.A503; Umar, U2,B014),
- hydrogen-fluorine bond as covalent (Kabul, K4.B220; Tajinder, T12.A103),
- hydrogen-fluorine bond as ionic (Kabul, K6.B363),
- lithium-iodine bond in focal figure 8 as ionic (Annie, A1.574 and A2.121; Brian, B1.322),
- silicon-oxygen bond as covalent (Jagdish, construct repertory test),
- silver-chlorine bond as covalent (Tajinder, T8.A537).

§A38.1.5: Brian, Quorat, Kabul.

Boron fluoride is an example of a substance where bonding would be expected to be polar according to CURRICULUM SCIENCE. Focal figure 14 represented a molecule of boron trifluoride as a resonance between canonical forms (where the individual bonds were shown as covalent or ionic in the individual canonical forms, but where the resonance implies the actual bonds are intermediate).



focal figure 14

In his first interview Brian described the bonding in boron trifluoride as ionic *and* covalent (B1.541). When Quorat considered focal figure 14 near the end of her first year of A level work she interpreted the canonical forms as showing bonding that was "covalent *and* ionic, because they seem to be attracted by ionic bonding, one of the fluorines" (Q3.B007). Quorat rationalised this as possible because "the boron can lose one electron to one of the fluorines, and it's still got two left which it can form covalent bonds with" (Q3.B030).

When Kabul was shown one of the three canonical forms in an interview near the end of his first year, he thought "it looks like covalent bonding" (K4.B352). From the diagram he thought there were *two* covalent bonds, and no other type of bond" (K4.B352). When he was shown a second canonical form Kabul again thought there was "covalent bonding" and no other kind of bonding (K4.B360). Despite this, when Kabul was asked about the 'F^-' in the figure he explained that boron "has got three valence electrons, so two of its electrons form a covalent bond with the fluorine and one of its electrons forms an ionic bond with the fluorine, so... it has lost one of the electrons, and fluorine has gained one electron, so fluorine becomes fluoride ion and boron becomes boron-plus" (K4.B363). He accepted "that seems ionic bonding ... between B^+ and F^-" (K4.B372). From a CURRICULUM SCIENCE perspective, one would not expect *some* bonds to be covalent and *some* ionic. Kabul was asked about this,

I: So which element is boron covalently bound to?
K: Fluorine.
I: And which element does it seem to be ionically bound to?
K: Fluoride [sic].
I: Right. So erm if you had some boron, and some fluorine,
K: Yeah.
I: and you reacted them,
K Yeah.
I: and if they produced some sort of compound,
K: Yeah.
I: do you think the bonding would be ionic or covalent?
K: It seems both.
I: But what do you think it would be, reacting boron and fluorine?
K: It would be covalent.
K4.B375

Despite the implication of the figure (and the weak electropositivity of boron, from group 3 of the periodic table), Kabul expected the bonding between boron and fluorine to fit the dichotomous category of *covalent* bond. When he was asked about the same figure in the third term of the second year of his course Kabul thought "probably it means that it's bonded covalently with two and ionically with one" (K6.B096). Kabul still did not suggest the bonding was polar, and now thought that if boron and fluorine were reacted to form boron trifluoride it would form "ionic" bonds (K6.B109).

§A38.1.6: Annie, Carol.

In chapter 11 (§11.6.2) it is suggested that there were occasions during the research where colearners were clearly not sure of the nature of a bond, but would still tend to prefer the covalent-ionic categories, and would not suggest 'polar', or 'something in between',

- Annie thought the bonding in aluminium sulphate could be "covalent" (A2.254) or "it could be ionic" (A2.256);
- Carol suggested that between an aluminium ion and a sulphate ion there would be "ionic bonding" (C1.457), although "it could be covalent actually" (C1.459);
- Carol was not sure what kind of bonds there would be in hydrogen fluoride - she would expect "well, ionic I suppose. Well, no, covalent I think" (C2.432).

In Carol's final interview she seemed to be using the concept of a polar bond, without producing the label 'polar', when she suggested that the bond in lithium iodide is "*probably covalent, but slightly ionic, kind of thing* ... Not pure covalent ... But not ionic" (C3.901-5).

§A38.1.7: Annie.

In chapter 11 (§11.6.2) it is suggested that it was also found that explicit reference to electronegativity or bond polarity might nonetheless be accompanied by a dichotomous classification of bond type.

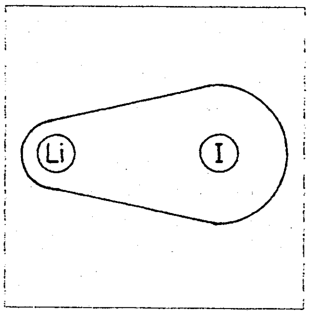
At the end of Annie's course she described the bonding in figure 8 as "ionic. Probably" (A4.284) because,

> "you've got a metal and a non-metal. And you're going to get complete transfer, of electrons from the lithium to the, iodine atom, and also, you can see there's *more of a pole*, on the atom."
> A4.286

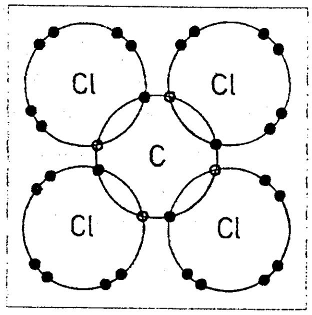
In her discussion of the figure Annie uses the terms "polarisation" and "molecule", but she feels the species is "ionic" (A4.292), not covalent (A4.294). When it is put to her that it might be something in between covalent and ionic, she accepts it "*could* be" (A4.296), although she "wouldn't have said it was" (A4.296). This was because of,

> "Something I think I know ... a metal and a non-metal. That's the way that they normally combine."
> A4.300-302

So here Annie's more established learning appears to take precedence when she has to classify the bond type.



focal figure 8



focal figure 3

§A38.1.8: Carol, Debra, Edward, Kabul, Quorat, Tajinder.

In Carol's first interview she described the bond between carbon and chlorine in tetrachloromethane as "a covalent bond" (C1.94) although,

> "something at the back of my mind says it might be an ionic, but I don't think it is. Because there's two, electrons being shared"
> C1.108

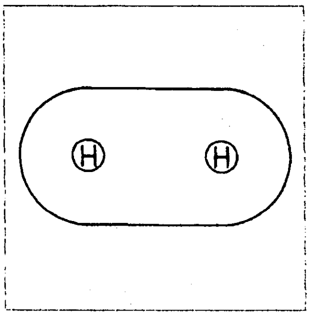
Despite the doubt, she did not consider the possibility of an intermediate type of bond. Although she was aware of the importance of electronegativity difference, she did not seem to accept the 'polar' categorisation, so that she thought "it's a *covalent bond, but* chlorine, has a ... *greater electronegativity* than carbon, so it pulls, pulls the two, electrons in that bond, nearer to it" (C1.124). Similarly, in a molecule of lithium iodide there was a bond (C1.405) and Carol knew the polarity of the bond, but did not know whether to use the category 'covalent' or 'ionic', and did not think to use any other option,

> "if it's covalent, it'll [i.e the electron cloud] be more over to the iodine side, but if it's ionic, then ... I still reckon it would be more over to the iodine side."
> C1.407

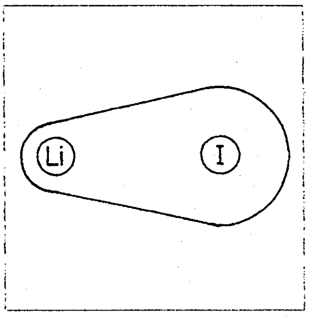
Carol also suggested that the bond between a sulphate anion and a cation was "covalent. But, not quite covalent ... in between, between ion, ionic and covalent" (C2.337) "covalent, but *like* polar" (C2.359) - although she concluded that as there were ions "it must be ionic bonding" (C2.361).

Debra was aware that electronegativity differences could lead to a dipole, but she still tended to classify the bonds dichotomously. She explained that focal figure 8 showed a “lithium atom, and an iodine atom, bonded *covalently*, with a *dipole*” (D1.325). Debra described this as “covalent” (D1.333) although “it’s not totally covalent or ionic, it’s somewhere in between” (D1.335).

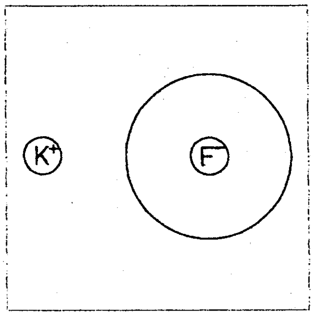
Edward also described the bond in focal figure 8 as “covalent” (E1.586), and the same as that in hydrogen (E1.588-90), despite having already referred to how “iodine has got a *greater electronegativity* than lithium, so attracts more of the bonding electrons” (E1.483).



focal figure 7



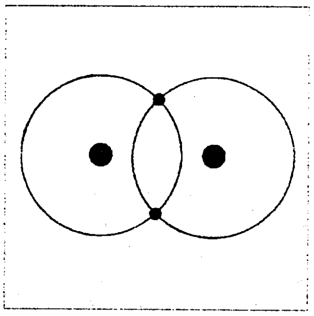
focal figure 8



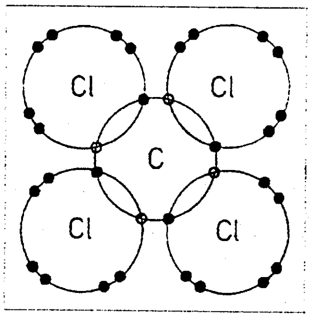
focal figure 9

When the bonding types in focal figures 7, 8 and 9 were reviewed, Edward continued to take the view that hydrogen *and* lithium iodide were covalent, and potassium fluoride was ionic. Only when he asked to physically sort the diagrams into two piles did he deduce “what you’re trying to get at” which was that “they’re not definite terms, they’re only ... irrelative [sic], ... they’re not definite and ... it’s like *a scale of electronegativity*” (E1.608-610).

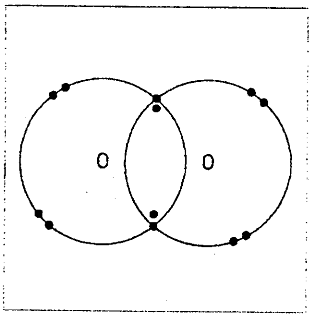
In Kabul’s final interview, during the last term of his course, he described the bonding in “a molecule of carbon tetrachloride” (focal figure 3) as “*covalent* bonds” (K6.A308). He thought that these bonds were similar to the bonds in hydrogen (focal figure 2), although different (K6.A308) “because one of the ... atoms can be more electronegative than another, so it tends to pull electron density more towards itself” (K6.A312). There then followed a long discussion of why chlorine might be more electronegative than carbon, after which Kabul reiterated that the bond was “covalent” (K6.A364). Kabul thought there was also a “covalent bond” in focal figure 4 (representing an oxygen molecule) which was similar to the one in focal figure 3 (K6.A366). Kabul considered that the bonds in focal figures 2, 3 and 4 were all covalent (K6.A389).



focal figure 2

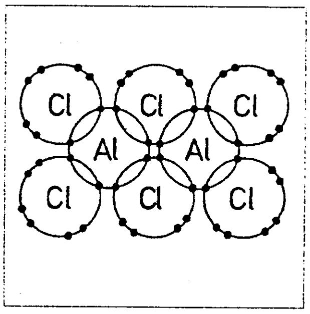


focal figure 3

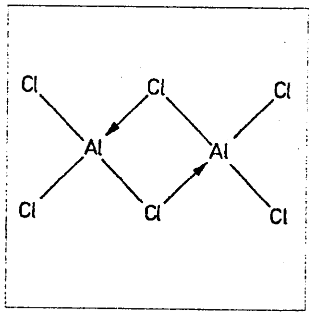


focal figure 4

In an interview near the end of the first year of her course Quorat described the bonding in focal figure 3 (tetrachloromethane) as "covalent bonding" (Q3.A175). She thought that the carbon-chlorine bond was not any different to the bond in focal figure 2 (the hydrogen molecule), as "there's still sharing" (Q3.A173).



focal figure 15



focal figure 16

When in Quorat's third interview she looked at focal figure 15 she thought that the bonding shown between aluminium and chlorine was "covalent bonding" (Q3.B038). In focal figure 16 she explained the dative bonds as the result of charges, "because the chlorine up here's *slightly negative* and the aluminium is *slightly positive*, so there's just a weak bond making them attract each other" (Q3.B069). However, despite the acknowledgement of charges in the molecule Quorat described the intramolecular bonding as "covalent bonding" (Q3.B069).

In his ninth interview Tajinder suggested the bonds in the ethanoate ion were "all polar bonds" (T9.B278). This even extended to the bond between the two carbon atoms,

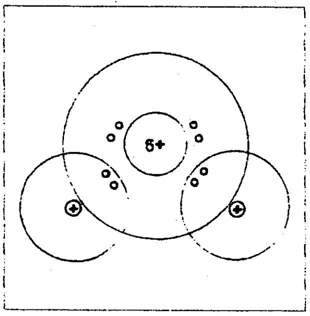
> "because I [had] thought that the carbon-carbon bond here would be covalent, but it wouldn't be, because then the influence of the other carbons around this carbon like changes the shape of that - so it wouldn't be ... it really depends what is, what is also like erm joined onto the carbon from the other side."
> T9.B333

Despite making this sophisticated observation, later in the interview Tajinder described the polar bond between aluminium and chlorine in focal figure 15 as covalent,

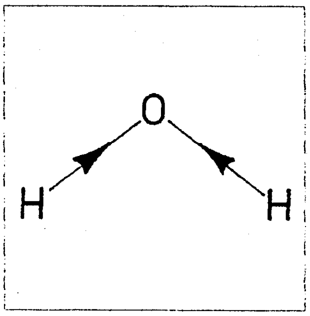
I: Do you think there's any bonding there?
T: Er, yeah.
I: What kind of bonding do you think there is there?
T: Hm, covalent.
I: Covalent bonding?
T: Yeah.
I: Right. Erm, are all those covalent bonds the same do you think?
T: Yeah.
T9.B390

On reflection Tajinder decided that he would expect the bonding between aluminium and chlorine to be "polar bonding" (T9.B427), but then when shown focal figure 16 he reverted to suggesting covalent bonding again,

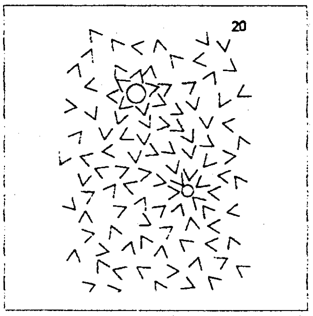
I: This is diagram 16. Do you think there's any bonding in that?
T: Mm.
I: What kind of bonding do you think?
T: Covalent bonding.
I: How many covalent bonds are shown there?
T: Six.
T9.B461



focal figure 19a



focal figure 19b



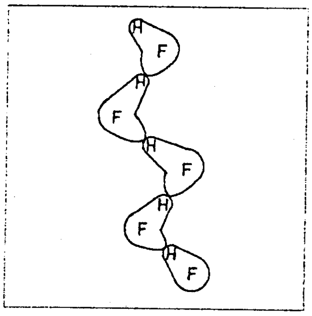
focal figure 20

When Kabul looked at the first part of focal figure 19, he suggested that it looked like "*covalent* bonding between two atoms" where "the smaller one looks like hydrogen, ... [and] the big one looks like oxygen" (K6.B220). He thought the second part represented "*covalent* bonding between oxygen and hydrogen, showing, showing that oxygen being *more electronegative* attracts the electrons more than hydrogen" (K6.B231). In focal figure 20 Kabul thought there were bonds "between hydrogen and oxygen in water" (K6.B266), and that these were "covalent" (K6.B270).

A similar pattern was found when Quorat discussed focal figure 19. She thought figure 19 part a showed "a *covalent* bond between oxygen and hydrogen" (Q3.B141), and that part b showed "A molecule of water, H_2O. ... With *covalent* bonds" (Q3.B148). Quorat knew that the arrows meant "that the electrons, the sharing electrons between hydrogen and oxygen are more distorted towards oxygen because it's more electronegative than the hydrogen" (Q3.B148), however, "they're *covalent* bonds, but it's polarised, so, you could say they're polar, no, you can't say it's polar, they're *covalent* bonds" (Q3.B154). Quorat went on to explain that she thought that *polar* bonds were *inter*molecular, "formed between different molecules" (Q3.B154). Quorat was apparently confusing polar bonds with dipole-dipole interactions, and she thought that "polar bonding is a kind of hydrogen-bonding" (Q3.B163). So although Quorat could discuss the polarisation of the bonds in water, and although she admitted a category of bonds she called 'polar', she did not feel the polarised bonds in the water molecule should be classed as polar.

§A38.1.9: Edward, Kabul, Quorat, Tajinder.

In chapter 11 (§11.6.2) it is suggested that even where colearners explicitly recognised the presence of hydrogen bonding, and explained that this implied a bond between hydrogen a more electronegative element, they might still label the intramolecular bond as covalent,



focal figure 11

Edward recognised that in focal figure 11 (a chain of hydrogen fluoride molecules) there was "hydrogen bonding" (E1.747) which was "the bonding that occurs between erm, hydrogen and the ... *electronegative* elements nitrogen, oxygen and fluorine" (E1.751). Despite this reference to the electronegativity difference, Edward went on to describe the bonding within the molecules as "covalent bonds" (E1.757), as the atoms "that are ... contained within each electron cloud, are covalently bonded to each other" (E1.771).

When Kabul examined focal figure 11 near the end of his first year, he recognised "*covalent* bonding between hydrogen and ... fluoride [sic]" (K4.B220). Although he also recognised the presence of "hydrogen bonding between fluoride of one and hydrogen of another", that is "between fluorine - and hydrogen of ... two molecules" (K4.B226), he thought the bonding within the molecule was a "covalent bond between hydrogen and fluorine" (K4.B232). This dichotomous description was not in keeping with his explanation of the hydrogen bond as "a bond hydrogen forms between it and *the more electronegative* element" (K4.B240). In his final interview Kabul again discussed focal figure 11, which he still recognised showed "hydrogen bonding in hydrogen fluoride" (K6.A507). Despite having previously discussed several examples that he had labelled as 'polar covalent' bonds in this interview, and again explaining that hydrogen bonding was "an intermolecular bonding" "formed between an *electronegative* element and hydrogen ..." (K6.A507), he again described the other bonds in the diagram as "a *covalent* bonding between hydrogen and fluorine" (K6.A518).

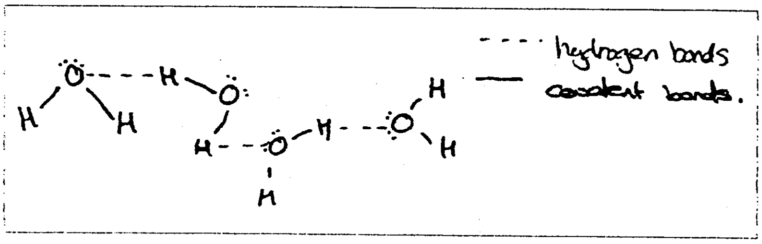
Quorat had studied bond polarity by her third interview near the end of her first year, and she was aware that in hydrogen fluoride there was hydrogen bonding "between the *negative* fluorines and the *positive* hydrogens" (Q3.A442). Yet despite this acknowledgement of the presence of charges, she still thought that the intramolecular bonding was *covalent*, the same type of bond as in hydrogen,

I: Are any other bonds shown in that diagram?
Q: *Covalent bonds* between erm h¬ hydrogen and the fluorine, of one molecule.
I: So there's two types of bonding shown there?
Q: Yeah.
I: So the covalent bonds there, are they just like the covalent bonds we've seen before?
Q: Yeah, they're just single covalent bonds.
I: So, the same as in figure 2, the hydrogen molecule?
Q: I mean they're not the same atoms, but yeah they're the same sort of type of bonding, yeah.
I: You would put them into the same category?
Q: Yeah.
Q3.A447

In Tajinder's twelfth interview, after explaining that the hydrogen bond in hydrogen fluoride was relatively strong because "fluorine is the *most electronegative* element, and hydrogen is *electropositive*" (T12.A069), he went on to suggest the bond in the molecule was *covalent* (T12.A103).

This tendency, found with the colearners Edward, Kabul, Quorat and Tajinder, was reflected in an answer given by a student in a mock A level examination. In the context of the bonding in ice, the student's acknowledgement of the presence of hydrogen bonding does not imply that the intramolecular bond will be labelled as polar.

In the following example this bond is described as covalent,



"Ice consists of covalent bonds between H-O in the atom [sic] and hydrogen bonds between H - - - O between two different atoms."
(A level student, response in A level mock, March 1994.)

§A38.1.10: Kabul.

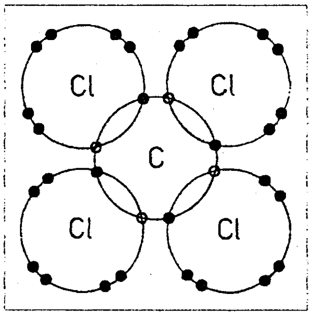
In Kabul's fourth interview he suggested that on fission of the carbon-chlorine bond in tetrachloromethane "one of the electrons would got to carbon and one of them would go back to chlorine" (K4.A353). Kabul was challenged, using the rhetorical device of 'some bright spark' who might suggest both electrons would go to the chlorine atom. This did not appear to be an option that Kabul had considered, and although he did not reject the possibility, neither did he accept this,

I: Some bright spark in the class comes along and says 'that's not what would happen, both of these electrons end up on the chlorine'.
• • • • [pause, c.4s]
K: I would ask why.
I: Erm, chlorine is more electronegative, pulls the electrons more.
K: Uh hm.
• •
K: But the electrons are also attracted to the carbon nucleus, isn't it?
I: Well they are, but chlorine's more electronegative, it's pulling them more.
• • •
K: (Mm.)
• •
I: How would you answer that?
• • • • •
K: Erm.
• • • • • • • • • •
K: No idea. I'll have to think about that.
K4.A387

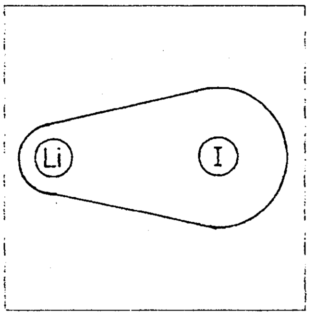
§A38.1.11: Paminder, Tajinder.

In chapter 11 (§11.6.2) it is suggested that the tendency to label bonds as covalent and ionic can co-exist with an ability to explain how the nature of a bond depends on the difference in electronegativity. So a student may classify a bond in a way inconsistent with their own explanation of how they classify bonds.

Paminder explained that in some cases this could be as a result of the way the bond was represented. In an interview near the end of the first year of Paminder's course she described the bond in the tetrachloromethane molecule as "covalent", although she thought that "the charge on the chlorine will be different to the charge on the carbon, so they're going to attract different electrons differently" (P3.A356). Later in the interview Paminder was shown focal figure 8 which she thought "seems to represent polar bonding", which was "another type of chemical bonding" (P3.A540).



focal figure 3



focal figure 8

As she had not mentioned this type of bond previously in the interview Paminder was asked if it was different to those already discussed. Paminder explained that it was the "representation" that was different, because on focal figure 8 the distortion of the electron cloud was apparent,

> "this *representation* is [different] ... 'cause this [focal figure 8] shows more that the electron clouds are distorted, there [focal figure 3] we were just considering, say the outer shells, like the outer valence shells, and [here] we're actually considering the electron cloud, and it's not as if one electron is completely transferred to the other one. It's like this seems to represent that the ... the iodine, it's electron cloud is a bit more distorted by the lithium, whereas on there we couldn't see the electron cloud..."
> P3.A540

When Paminder was asked about these two types of diagram, she explained that the polarity of the bond was explicit in focal figure 8, which overcame the tendency to use the covalent-ionic dichotomy,

> "you couldn't tell if there was polar bonding there [on diagrams such as focal figure 3] you'd, *you're under the influence that it was ionic or covalent*, but on this one [focal figure 8] it's more obvious that it looks as if it's polar bonding"
> P3.A550

So Paminder 'knew' that bonds such as C-Cl and Li-I were polar, but without an explicit visual cue, such as the asymmetric electron cloud in focal figure 8, her thinking would be channelled towards the more familiar categories, as she was "under the influence that it was ionic or covalent", the influence of her dichotomous classification.

In the examples quoted above of colearners Carol, Debra and Edward classifying the bond in focal figure 8 as covalent, the visual cue of the asymmetric electron cloud was not sufficient to overcome this influence. In the following examples from Tajinder's case two compounds were being discussed in abstract, without any focal diagram.

In an end-of-term test Tajinder suggested that a material he expected to have covalent bonding was calcium chloride, and this was followed up in the second interview (T2.A380). This interview took place shortly after Tajinder had been studying the use of electronegativity values to predict bond type in class, yet when he was asked he still suggested calcium chloride would be covalent,

I: Can I ask you about calcium chloride, as a substance? What kind of bonding would you expect to be in calcium chloride?
• • [pause, c.2s]
T: Erm, covalent.
I: Why would you think covalent?
• • • • •
T: Erm
• • •
T: erm (ca-)
• • • • •
T: Erm,
• • • • •
Why would I think that?
I: Yeah. How, how do we decide whether something is going to be covalent of ionic if we don't know?
T: Well, what we done yesterday, we could er draw it out, and write all the electronegativity values, and then see whether, it was high or low and if it was high that showed ionic bonding, and if the difference was low then it was covalent bonding.
...
I: Is chlorine highly elec-, high electronegativity, or low electronegativity?
T: Chlorine?
I: Mm.
T: Erm, that's quite high.
I: What about calcium?
T: That's quite low.
I: Quite low. Would you expect the difference to be quite large, or?
T: Er, I would, actually.
I: Yeah, what kind of bonding does that suggest?
• •
T: It should suggest ionic.
...
I: Do you still think it's covalent?
T: Erm,
• • • • • • • • • • • • • • •
T: er
• •
T: yeah, I do.
T2.A380

So Tajinder 'knew' that according to the rules he had studied, the bonding in calcium chloride should be - at least predominantly - ionic, but he already believed the bonding was covalent. It was his preexisting belief which led to his initial response, *and* to his considered opinion, not his recent learning. In his eighth interview there was a similar exchange when suggested silver chloride would be covalent. However by this stage of his course Tajinder had learnt that "normally compounds are polar which is something in between" covalent and ionic (T8.A560). Despite this Tajinder began by suggesting silver chloride is covalent, (T8.A537). When he is asked how one might predict the kind of bonding, Tajinder explains,

> "electronegativity values. ... because hydrogen, if you react hydrogen and fluorine, that's highly [sic] positive, highly positive highly negative, and you can work out the electron density like that, how much the electrons are attracted to one side of one atom rather than the other. ... And if, if they are, they're more, the more they're attracted to one side, say it was like that, and that would show pure ionic bonding, not pure, but more ionic bonding because the electrons are attracted to one side more than an other, and if you have erm, this is erm high high covalent bonding, because, because they're the same type of atom, they have equal pull on the electrons, showing the electron density is smeared out equally,showing it is covalently bonded, but normally compounds are polar which is something in between."
> T8.A560

Tajinder knew that covalent bonding was found "when the values are equal to one another, electronegativityvalues", and ionic bonding "when electronegativity values is much higher than the other" (T8.A560). He suggested "NaCl" as an example of an ionic material "because erm sodium has got - got a low electronegative value, and chlorine has got a very high electronegative value, so the difference is relatively high, so therefore it shows if its higher then there's quite a lot of ionic, there's more ionic bonding, tendency" (T8.A587).

However Tajinder did not know the values to make a decision about silver chloride, so he decided,

> "I think it might be covalent, because erm, ionic compounds normally dissolve in polar solvents, whilst erm, - covalent compounds don't, and this is a polar - polar com¬, polar solvent water that we're using, so if it was ionically bonded, it would melt, it would dissolve. But it forms a precipitate."
> T8.B003

The point of most significance here is that in the absence of the electronegativity values that Tajinder felt provided the most appropriate criterion, he did not class the bond in silver chloride as 'polar' which "normally compounds are", but rather only considered the possibilities of 'covalent' and 'ionic', and selected the category of 'covalent' bond, which he had suggested only applied when "they're the same type of atom".

§A38.1.12: Debra.

In chapter 11 (§11.6.2) it is suggested that where the concept of bond polarity *is* used in classifying a bond, it may be used as a moderator to the primary classes of covalent and ionic. For example in her second interview Debra described the bonding in tetrachloromethane as "covalent bonding between the carbons and the chlorines" (D2.101), where she defines a covalent bond as "where a pair of electrons is shared between two atoms, more or less equally, [which] probably have similar electronegativity values" (D2.109). She explained that this would hold the atoms together as "they gain the full shell then, so they're stable molecules, so it's sort of desirable to be like that" (D2.111). So Debra explained the bond in terms of the FULL SHELL EXPLANATORY PRINCIPLE, and described the bond as 'covalent' even though she herself introduced the notion of electronegativity. Only when Debra was specifically asked if carbon and chlorine did have similar electronegativities, did she report that "chlorine would be *more electronegative*" (D2.149). She thought that the bond would "have *some covalent character*" (D2.151) although "the chlorine will have more of a hold over the electrons, and so the bonds will be *slightly polar*, towards the chlorine" (D2.153). She thought the molecule was "*not completely polar*" (D2.233) as "it's got *some covalent character*" (D2.235). So for Debra the polarity of the bond was a secondary effect, which moderated the covalent bond.

§A38.1.13: Kabul.

In Kabul's fourth interview he spontaneously suggested polar bonding when asked to list the types of bonding he was familiar with. However, this bonding type was modelled around the familiar covalent category, so that,

> "[polar bonding is] *similar to covalent bonding*, but one of the species, is more electronegative, so it tends to, you know, pull electrons towards itself. The electrons ... aren't symmetrical in the centre ... [rather] they *share* most of the time around one atom, the one which is more, more electronegative."
> K4.A072

As an example of a substance with this type of bonding Kabul gave "hydrogen chloride", where the electrons would be nearer the "chlorine, chloride ion [sic]" (K4.A083). However, when he was asked about focal figure 3 (representing a molecule of tetrachloromethane) Kabul thought the bonding looked "like covalent", which was the same bonding as in figure 2 which represented a molecule of hydrogen (K4.A271). Later, however, although he still thought the bonding was covalent, Kabul suggested that "[in hydrogen] the bonding seems to be between two atoms of the same type, [whereas in focal figure 3] it seems to be different, ... the electrons originate from ... atoms of different elements" (K4.A298) He suggested that this did "not really" make a significant difference, although "there will be some ... polarity" (K4.A298). He said this did "not [have] much" effect, but "chlorine [is] more electronegative than carbon, so it may tend to attract electrons more towards itself" (K4.A305). Kabul thought "the force from the electron to chlorine will be more than from electron to carbon, 'cause chlorine is more electronegative" (K3.A335). At this stage in his course then Kabul seemed to construe polar bonds as modified, indeed slightly modified, covalent bonds.

When Kabul was shown focal figure 13 (the ethanoate ion), he described the bonds as covalent (K4.B290). He thought all the bonds were covalent, although not all the same as "between carbon and oxygen there will be *polar covalent* bonding" (K4.B294).

Near the end of the first term of his second year (December, 1993) Kabul was recorded discussing past examination questions with Tajinder. In the transcript extract below Tajinder suggests the need to distinguish between covalent and polar bonds, but Kabul suggests that 'polar bond' falls within the category of 'covalent bond',

T: All right then [reading:] 'what's what's meant by the term covalent bond?'
K: I think covalent bond's just due to the sharing of electrons.
T: Yeah. Does that get you - two marks?
K: Nearly, yeah.
T: {laughs} Erm.
K: Give an example like, so you've drawn chlorine, > chlorine. >
T: < Yeah. < Do we need to say why it's a covalent bond and not - erm - polar.
K: Well *polar bond is part of covalent bond.*
KT1.A047

When, in his final interview, Kabul was shown focal figure 8 he thought this represented a "polar *covalent* bond" (K6.A451), which he compared to a covalent bond. It was,

> "*like a covalent bond*, but, one of the atoms, is, has got a smaller charge, you know, because it's more electronegative or more electropositive, you know, compared to [the] other atom, so it tends to attract electrons more towards itself compared to other atom. So, [in] this example, iodine is more electronegative than lithium, so it tends to attract electron cloud more towards itself, and since most of the electron density is around iodine, it tends to have you know a small ∂- charge, and lithium acts as if it has lost the electrons you know, so there is a small ∂+ charge"
> K6.A453

So Kabul's response was initiated from his concept of a covalent bond, and then he explained how - from that starting point - the result was "a small ∂- charge" on iodine, and "a small ∂+ charge" on lithium. From a comparison with the covalent bond, the explanation moves to a comparison with the ionic case, so that "lithium acts *as if* it has lost the electrons". By contrast, the next focal figure shown to Kabul, figure 9, represented "a *proper* ionic bond" (K6.A462) where "potassium, being very electropositive, and fluorine, being very electronegative, fluorine attracts the electron *completely* from potassium, so there are ... no outer electron around potassium any more, they're all around the fluorine atoms, so [potassium] has completely lost the electron" (K6.A465).

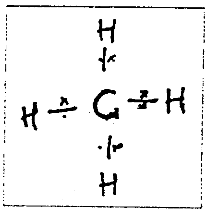
So during the period from the end of his first year, to the end of his course, Kabul variously suggested that,

- polar bonding is similar to covalent bonding;
- a polar covalent bond is like a covalent bond,
- the polarity of the carbon-chlorine bond did not really make a significant difference nor have much effect;
- carbon-oxygen bonds were polar covalent bonds;
- the category 'polar bond' is part of 'covalent bond'.

§A38.1.14: Tajinder.

In Tajinder's eighth interview he had drawn a figure to represent covalent bonding, and had explained,

> "covalent bonding is where electrons are shared between an atom and another atom, and not transferred as in ionic bonding. And in ionic bonding you form positive and negative ions, and this is not the case in covalent bonding because an electron is not totally given away to another atom, it's always shared, so ... if you say you had methane, yeah, it's sharing its bonds with hydrogen. ... Hydrogen can form one bond and carbon can form four bonds, so four hydrogens connected with the carbon and the electrons are shared in that bond"
> T8.A160

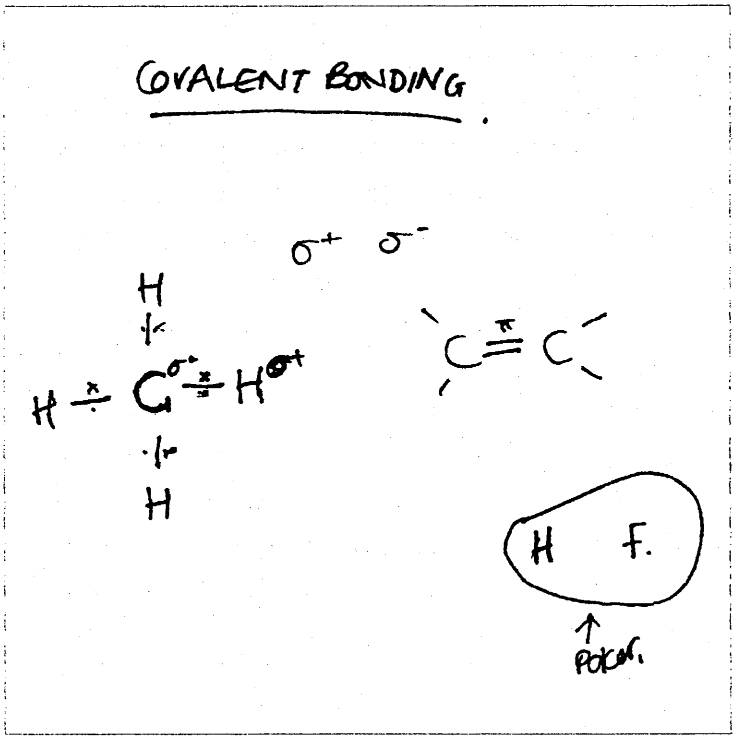


Tajinder's representation of covalent bonding (detail) during interview T8.

Later in the interview, after a discussion of the role of electronegativity values in discussing bonding type, Tajinder was asked once again about his diagram.

> I: So what is a covalent bond?
> T: Sharing of electrons.
> I: Right, so these dots and crosses are they the electrons being shared?
> T: Yeah.
> ...
> I: Where is the bond between that hydrogen and that carbon?
> T: Well, erm, it's, this is the whole of the bond, but erm, but when we was talking about electronegativity values we said that if, if one, if one was erm, if one was much higher than the other ... If there's hydrogen and fluorine, that's more, much more electronegative than that one, therefore it's got a greater attraction for the electrons, so the bond will look something like this. [sketching shape of HF molecule]
> I: So would that be a covalent bond?
> T: This will be a polar bond.
> T8.B471

As this exchange took place Tajinder drew a molecule of hydrogen fluoride with an asymmetric electron cloud,



Tajinder's representation of covalent bonding, including a polar bond (detail)

This consideration of polar bonds led to Tajinder deciding the bonds in methane could be considered polar,

> "we can't actually say these are covalent bonds then, pure covalent, we can say these are polar bonds, couldn't we - because carbon and hydrogen haven't got the same electronegativity values, have they? ... They might be similar, they'll be similar, but not erm the same. So that's why they form - covalent bond, so-called covalent bonds, and erm, the attraction, whichever, the electronegativity values which vary, show which one has a greater attraction is to pull in the electrons, so if it was carbon, then ... they're pulled in more toward the carbon than towards the hydrogen."
> T8.B483

However, Tajinder's description of the bonds as polar did *not* mean he no longer classed them as covalent,

I: So is that a covalent bond in carbon and hydrogen, in methane?
T: Mm.
I: But did you say it was also a polar bond?
T: Mm.
I: So it can be both of those things?
T: Mm.
T8.B501

§A38.1.15: Brian, Carol, Umar.

There was evidence in the study that other colearners also used the 'polar' label less as a category in its own right, but more as a moderator for the covalent and ionic categories. In the following examples various ways are used to express polar bonds as modified covalent or ionic bonds,

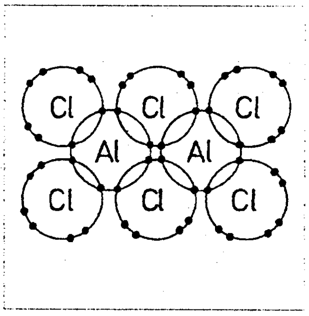
- the lithium-iodine bond was "a *polarised covalent* bond" (Brian, B1.330);
- the bond between lithium and iodine was "a covalent bond, but it's *trying* to be ionic ... because ... the iodine has a greater electronegativity (Carol, C1.473-9);
- the bond between lithium and iodine was either "ionic" or "a covalent bond that's slightly polar" (Carol, C2.273-5);
- bond between a sulphate anion and a cation would be "ionic but *trying* to be covalent" (Carol, C1.487);
- the bond in the hydrogen fluoride molecule was "covalent, *trying* to be ionic, because it's got that funny shape again" (Carol, C1.536)
- the bond in molecular iodine was "covalent *trying* to be ionic" (Carol, C1.850);
- the bond between carbon and chlorine was "covalent" but "slightly polar" (Carol, C2.52-4);
- "a covalent or ionic bond can be polar if the elements of the atoms have a large e-vity difference" (Umar, revision exercise: concept map on chemical bonding, June 1993).

§A38.2: Learners' classification of dative bonds.

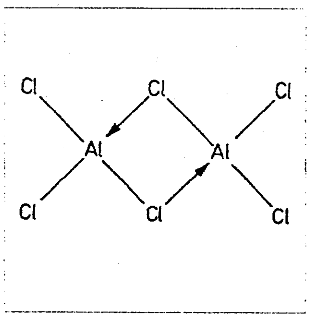
In chapter 11 (§11.6.3) it is suggested that in this research it was found that dative bonds were often considered by colearners to be *covalent* rather than *polar*.

§A38.2.1: Brian.

Sometimes in the interviews the colearners simply described dative bonds as covalent. In Brian's second interview he described the bonds in aluminium chloride as "covalent" (B2.166). He recognised that some of the bonds shown in the dimer (focal figures 15 & 16) were "dative bonds" (B2.188), where "the chlorine *donates* one, *gives* one pair of electrons, to form a bond, with the aluminium" (B2.190), but he still classed this as "covalent" (B2.192) rather than polar.



focal figure 15



focal figure 16

§A38.2.2: Noor.

In a concept map prepared as a revision exercise at the end of the first year of Noor's course she explained why dative bonds form in beryllium chloride. Her explanation was based on the OCTET RULE EXPLANATORY PRINCIPLE Noor describes the bonding between beryllium and chlorine as "covalent", and describes the dative bonds in terms of "sharing",

> "Covalent bonding is associated with sharing electrons ... A dative bond is when eg $BeCl_2$ although $BeCl_2$ is now covalently [sic] bonded it still requires (ie Be) 4 more electrons to obtain a full outer shell. It obtains these by *sharing* with the surrounding Cl atoms."
> (Noor, concept map on chemical bonding, June 1993.)

§A38.2.3: Jagdish, Kabul, Umar.

On other occasions dative bonds were presented as *similar to* covalent bonds. So, in Jagdish's third interview she discussed the 'dative bonding', which occurred in "a compound of ammonia" (J3.A280) because "it's got a lone pair of electrons" (J3.A287). However, she was only able to explain this in terms of a sharing model, rather than an electrostatic interaction. So dative bonding was "*similar to covalent bonding*, where you've got the share of electrons, but instead of getting like equal amount of electrons from each, element to share, only one of the types gives the electrons for the other one to share as well" (J3.A280).

Kabul was first recorded referring to dative bonding in his fourth interview. He seemed to see dative bonding as an instance of covalent bonding which "occurs when the *sharing* pair of electrons originate just from one atom", such that "once it's formed there *isn't much difference* between covalent and dative bonding" (K4.A049). When he was shown focal figure 15 Kabul though the bonds represented were "covalent" (K4.B399), with "four covalent bonds between each aluminium and chloride ion [sic]" (K4.B399). Kabul explained the apparent violation of valencies in terms of it being "similar to beryllium chloride ... polymer, ... in which dative bondings have been formed" (K4.414). In the aluminium chloride,

> "Let's say aluminium is forming three bonds with chlorine. Aluminium is 2.8.3 ... so ... aluminium is forming three bonds isn't it? So in total aluminium has a valency of three, it forms three covalent bonds. So in total aluminium has got six electrons. ... Three and one from each atom. But in order to go to, you know, G.C.S.E. format, which says, ... in order to attain a stable state you must have eight electrons, so one of the chlorine atoms seems to donate two electrons, and *form a dative bond, which is just similar to covalent bond* once it's formed."
> K4.B414

So rather than seeing dative bond formation as an electrostatic interaction between the positive, incompletely shielded, beryllium core and a lone pair of electrons on chlorine, which might have led him to consider the polar nature of the aluminium-chlorine bonds, Kabul explained the interaction in terms of aluminium obtaining an octet, and concluded that the bond was "just similar to [a] covalent bond" (K4.B414).

In an interview near the end of the first year of Umar's course he had available a category of bond called 'dative', but he explained this in terms of sharing electrons as in a covalent bond, as "it's *like covalent bond*, like one of the atoms donates both the electrons that are shared, instead of one electron from each atom, shared" (U3.A073).

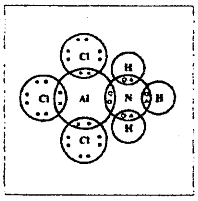
In a concept map prepared as a revision exercise at the end of the year Umar again described dative bonding in terms of sharing, as "a bond in which the e^- *shared* are from one of the atoms only" (concept map on chemical bonding, June 1993).

§A38.2.4: Lovesh, Tajinder.

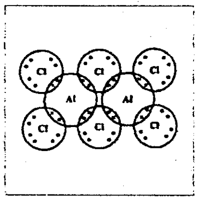
Another variant for describing the dative bond was to construe it as *a type of* covalent bond. In a concept map prepared as a revision exercise near the end of his first year Lovesh categorised dative bonds as covalent, stating "dative bonding is a *type of covalent bonding* but involves the lone pairs of electrons" (June 1993).

During his final interview, Lovesh classified some bonds in focal figure 15 as covalent, and others as polar, although in both cases the bonds concerned were between aluminium and chlorine, so "there's a polar bond between erm aluminium and three chlorine atoms, and there's also a *dative covalent* bond, between one of the chlorines of the other atom [sic] and a, and an aluminium of the other one" (L4.A498). It might have been expected that if the Al-Cl bonds were to be perceived differently, then the dative bond (where both electrons originate from one atom, and may be seen as donated by, or even belonging to that atom) might be seen as *less* covalent. However, Lovesh thought that a dative bond was a type of covalent bond: “a dative covalent bond is when erm, a lone pair of electrons are *shared* between two atoms. And it’s *a form of covalent bonding*” (L4.A533).

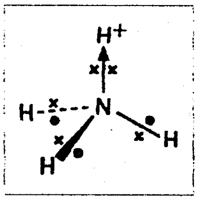
When Tajinder was pressed on the distinction he suggested that “once a dative bond is formed you can’t distinguish ... so they’re all covalent bonds” (T12.C216). But he also tended to label dative bonds as ‘dative covalent’. In his 22nd interview Tajinder compared three chemical species using the triad cards (elements 249, 338 and 339).



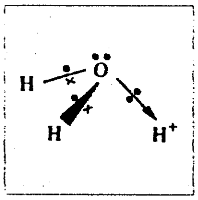
triad element 339



triad element 249



triad element 179



triad element 328

He explained that in triad element 339 there was a “dative covalent” bond,

> “I think it’s called an adduct, where a *dative covalent* bond takes place, this is because $AlCl_3$ exists as a molecule, and so does ammonia and aluminium like we was talking about before wants a full octet, which is in this case [sic] is eight electrons, and the ammonia has got a lone pair of electrons”
> T22.A366

When he considered triad element 249 Tajinder explained that “this is the same sort of thing ... and this has also formed a *dative covalent bond*, and, in order to form a full octet for each of the species involved” (T22.A471). He later comments that “these two are both *dative covalent* bonds” (T22.A481). Tajinder also identified *dative covalent* bonds in triad element 179 (T22.B207), and in triad element 328 (T22.B248). He later opined that “there’s not any difference is there, once a dative covalent bond is formed, there’s not any difference between [to] a pure covalent” (T22.B328). Tajinder repeated this point in the next (and final) interview, saying “it doesn’t make any difference ‘cause once a dative bond is formed it’s it’s the same as a covalent bond” (T23.B123).

It would seem that there is little substantial difference between learners seeing a dative bond as covalent, as a type of covalent bond, or like covalent. Whichever of these descriptions is used, the inherent polar nature of the dative bond is ignored. From the CURRICULUM SCIENCE perspective, the dative bond is a special case of the polar bond, and colearners’ dichotomous classification of dative bonds is a special case of the tendency for polar bonds to be seen as either covalent or ionic, or as slight modifications of these archetypes.

Appendix 39.

Evidence of octet thinking: learners' dichotomisation of bonds that do not fit on the covalent-ionic continuum.

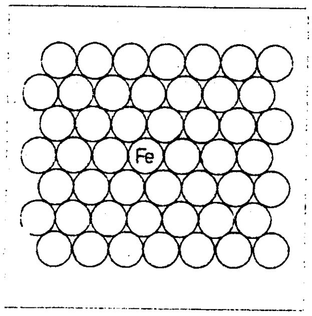
§A39.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, subsections §11.6.4 and §11.6.5.

§39.1: Learners' classification of metallic bonds.

The FULL SHELLS EXPLANATORY PRINCIPLE can not be used to explain the metallic bond in terms of a simple pithy description such as sharing or transferring electrons (as in the covalent and ionic cases respectively).



focal figure 6

It is reported in chapter 11 (§11.6.4) that data collected during the research suggest that colearners' explanations of metallic bonding tended to fall into four general categories:

- there is no bonding in metals;
- there is some form of bonding in metals, but not proper bonding;
- metals have covalent and/or ionic bonding;
- metals have metallic bonding, which is a sea of electrons.

Some of the colearners displayed several of these interpretations at various stages in their course.

§A39.1.1: Annie.

For example each of these positions, and others, were elicited from Annie as she attempted to make sense of metallic bonding. So at the time of Annie's first interview she did not seem to have a class of bonding relating to the CURRICULUM SCIENCE category of metallic bonding. Annie thought that the circles in focal figure 6 were "iron atoms within an element" (A1.285) "all close together" (A1.289), which hold together (A1.295) because "they're all the same sort" (A1.297). According to Annie "they're all the same and don't need to be bonded" (A1.301). By the time of her second interview Annie was open to the idea of there being bonding in iron. However, she appeared to have no stable view on this, as over the course of a few minutes (A2.55-107) she suggested that the iron

- had no bonding,
- had hydrogen bonding,
- was just an arrangement,
- had hydrogen bonding which was van der Waals forces,
- had van der Waals forces which were different to hydrogen bonds,
- had metallic bonding, and,
- had van der Waals forces which were not the same as metallic bonding

At the start of her third interview Annie added a further variation when she commented that sodium was "held together by *ionic bonds*, within the lattice" (A3.2). She later explained that in metals there was "metallic bonding, which basically holds the atoms sort of above and below, together" (A3.402). Annie's description of metallic bonding implied that it was somehow a lesser type of bonding, as, "the atoms, are sort of held by metallic bonds, although basically the bonds are *just* sort of held, holding them altogether rather than, *rather than combining them to form something*" (A3.408). Annie appeared to be attempting to understand the metallic bond in terms of the more familiar categories of covalent and ionic bonds. So she thought that the metallic bonds are "sort of *like ionic* in a way, 'cause one metal sort of donates to another, but it occurs in metals and it won't occur between ... a p-block [element] and an s-block [element]" (A3.416). However, "they're not sort of *really sharing*. And they're not *really combining*, because you're not making sort of a separate molecule, so although they are sort of like all held together, there is something going on, although, it's not really, *you can't really class it as ionic bonding or, covalent*" (A3.426). Annie's final interview took place two weeks later, and after a tutorial intervention informed by her comments in the previous interviews. After this tutorial Annie seemed able to describe the metallic bond in much more detail,

> "you've got delocalised electrons going round, the metallic atoms, in a sort of like a sea. So they're, they're all sort of freely flowing around ... [as] metals haven't got full outer shells, then by electrons moving around, they're, they're getting, a full outer shell, but then they're sort of losing it, but then like the next one along will be receiving a full outer shell. So, you've also got charges, that are forces from the nucleus pulling, just attracting ... electrons from outside in. But mainly due to, like delocalised electrons they can move about, so, then you've got forces keeping, keeping it all together" (A4.84)
> A4.82-4

Despite this explanation (using a mixture of full shell and electrostatic ideas) Annie thought that, "you haven't got *like actual bonds* in metallic bonding" (A4.82). By 'actual bonds', she appeared to mean something that she could recognise as either covalent or ionic, "there's still bonds, but, not in the sense of like *covalent or ionic* bond, you're not getting electrons *completely transferred or shared*, between the two. It's not as definite" (A4.90). One could paraphrase this by suggesting that, for Annie, a metal did not contain 'proper bonds'.

§A39.1.2: Jagdish, Noor, Kabul.

From a CURRICULUM SCIENCE perspective Annie's first notion that metals did not have any bonding seems inconsistent with the obvious structural integrity of common and familiar metals such as iron and copper. However Annie felt bonding was not needed, and in Jagdish's first interview she also thought that focal figure 6 showed "just a lot of iron atoms" with no bonding present (J1.A249, A263). Jagdish was asked to reconsider whether there was any bonding in the iron metal. She concluded that "there can't be. ... No, I think it's just formed like this", although she did think the iron atoms stuck together (J1.A326). This answer may not seem sensible, as from a CURRICULUM SCIENCE viewpoint something (*i.e.* bonding) should be responsible for the cohesion. On further questioning Jagdish decided that metals did have bonding (J1.A270), but not covalent, rather "metals have ionic bondings" (J1.A274), again suggesting that metallic bonding was understood in terms of the models of covalent and ionic bonding the learner had available. However, when asked to elaborate Jagdish suggested that in the case of focal figure 6 "the iron atoms lose electrons, and they form positive ions", and the electrons go to "non-metals" which were not on the diagram (J1.A284). Although Jagdish recognised that there were only iron atoms present, the electrons "wouldn't go to another iron" but "to a non-metal", and for this to happen "there'd have to be some, something like heat or something too, for the reaction to happen" (J1.A316). In this section of the interview it may be seen that Jagdish initially denied there was any bonding in iron, but - when realising from her own experience that iron had structural integrity - she changed her mind. She thought that this bonding would be ionic, and the iron would act as the electron donor. An electron acceptor would then be needed, so there must be a non-metal involved, and energy was required to initiate the reaction. It is possible to make some sense of this if it is assumed that Jagdish only had available two categories of bond and thought that metals could be involved in ionic but not covalent bonding. Her informal knowledge of iron suggested some bonding was needed, and as iron was a metal this had to be ionic, which would involve reaction with a non-metal. Clearly Jagdish's existing knowledge channelled her thinking away from the context of the original problem (bonding in *elemental* metal iron).

In Noor's first interview she described focal figure 6 as "an arrangement of atoms, iron atoms", and she did not think any bonding was represented (N1.A427). Noor thought "there must be something" in the sense of an interaction between the iron atoms, although she did not "think there's any chemical bonding" (N1.A481),

I: But is there any chemical bonding there?
• • • • • • [pause, c.6s]
N: I don't think there's any chemical bonding.
I: In number 2,
N: Mm.
I: you said there was some bonding, didn't you? What kind of bonding was that?
N: Covalent.
I: And what did you tell me covalent bonding was?
N: Sharing of electrons.
I: And in number 5, I think it was, you said there was some bonding.
N: Yeah.
I: What kind of bonding was that?
N: Ionic.
I: And what did you say that was?
N: Transfer of electrons.
I: Okay, and have you got any covalent bonding in number 6?
N: No.
I: Or any ionic bonding?
N: Nope.
I: So, is there any other kind of bonding you can have?
N: Don't think so.
N1.A481

Noor, then, did not think the bonding in a metal was covalent or ionic, and she did not know of any other class of chemical bond. So although she thought there had to be something holding the metal together, she concluded it could not be chemical bonding.

When during Kabul's first interview he was shown focal figure 6 he identified it as "iron" but did not think it "look[ed] like" there was any bonding in the substance (K1.A349). He thought "there should be bonding but it doesn't look like it" (K1.A358), presumably due to the absence of a graphical cue such as overlapping atoms.

§A39.1.3: Carol, Debra, Edward, Kabul, Mike, Paminder.

Similarly, in Carol's first interview, she did not appear to have available a category of metallic bond. She thought that there had to be some form of bond in iron,

> "or it wouldn't be held together, would it? I reckon, if they didn't have any bonds then the circles would be spread out, and it would be like, liquid or something? I reckon it's a solid because they're close together, and it's closely packed, and its looks as though it could be in a kind of lattice, and that's what solids are, in a lattice"
> C1.298

Carol suggested that these bonds in a metal would be "covalent" (C1.300). In Debra's first interview she thought that the bond in a metal (focal figure 6) comprised of the atoms "sharing electrons, pair of electrons and there's free electrons, within the metal, that are free to move" (D1.266). The 'sharing electrons' component was covalent (D1.270), and the "electrons that are free to move in the substance, and they're attracted to the positive" (D1.272) was a second type of bonding (D1.278) which was "like ionic" (D1.280). So Debra's conceptualisation of metallic bonding was in terms of the covalent and ionic categories.

In Edward's first interview he described focal figure 6 as "an example of metallic bonding, close packing. Basically how marbles would arrange themselves if you put them into a solid container" (E1.457). The bonding was,

> "*similar to ionic bonding*, in the fact that you've got, positive and negatives ... and the electrostatic ... attraction between the two, because you've got the metal positive ions in the lattice, held together by their attraction for the pooled electrons."
> E1.461

These 'pooled' electrons were "sort of moving around the positive ions", and Edward labelled them "delocalised" (E1.463), although he was working from a comparison with the ionic case.

In Kabul's second interview he was asked about a question in a class test where he had suggested cobalt as a substance with a giant molecular structure (c.f. appendix 35, §A35.3.1). Kabul thought a giant molecular structure was "a macromolecule ... in which there are strong covalent bonds" (K2.A542). When asked if cobalt had strong covalent bonds he replied that there were "strong *metallic* bonds", but he still thought cobalt could have a giant molecular structure (K2.A542) as in cobalt "strong *covalent* bonds exist between ... the molecules" (K2.A561). Later Kabul suggested that cobalt "doesn't form a molecule" (K2.A572), *but* he thought that in cobalt "there are strong *covalent* bonds" between cobalt molecules (K2.A581). Kabul was only able to define a molecule as "build up of atoms" (K2.B025), and he thought cobalt "could be" molecular (K2.B025).

In his last interview, in his final term of the course, Kabul referred to metallic bonding as being "*similar to covalent* bonding", in that their "outermost ... electron shells, they overlap with one another and you know they become attracted" (K6.A401). (From an integrated electrostatic/orbital perspective this description could be seen to apply to all forms of bonding, not just covalent.) He also suggested that an iron atom was stable "because iron has got ... a lot of d electrons in there, ... [and] it's difficult to lose all the electrons" (K6.A426), which was what Kabul thought was what iron would have to do to react (K6.A433). So at this point Kabul appeared to be thinking that iron could only react by forming ionic bonds. It would seem that during his course Kabul's concept of metallic bonding developed considerably, but remained closely associated with his preexisting categories of covalent and ionic bonding.

In Mike's first interview he suggested that focal figure 6 showed "a block of iron atoms joined together", where he thought the bonding "would be covalent bonding", although he was not sure (M1.A436).

When Paminder was interviewed for the first time she thought there would be some sort of bonding in iron, but she had no category of metallic bond. She thought focal figure 6 "looks like lots and lots of iron atoms", and "they're all stuck together, so there must be something holding it together" (P1.B059). Paminder was reluctant to suggest what type of bonding might be involved, and when bond types that had previously been elicited were presented with the alternative of 'something else', she selected ionic bonding,

I: Does anything hold the atoms together?
P: Well it must do or it would fall apart. {laughs}
...
I: So, there's something holds them together?
P: Yeah.
I: Some sort of bond?
P: Yeah, I think so.
I: Chemical bond?
• • [Pause, c.2s}
I: Might it be covalent? Or ionic? Or single, or double, or something else?
• •
P: Yeah it could be, it could be covalent or ionic. Ionic, I think, because you know it is a two-plus, and two-plus that indicates that it is not covalent, it's ionic, {laughs} so.
P1.B167

There was no indication in figure 6 that iron was 'two-plus', but Paminder recalled this association, and for her this was consistent with ionic bonding.

§A39.1.4: Incidental data.

The tendency to explain metallic bonding in terms of the more familiar models of ionic and covalent bonding was also reflected in a comment that "metals have a molecular structure" made by a student commencing A level in an induction exercise (September 1990). Indeed, even after teaching students may retain this approach to metallic bonds,

> "In metal the electron are Covalently bonded."
> (A1 chemistry student, assessment response, February, 1996.)

> "Metals are good conductors because they contain only a few co-valent bonds, mainly ionic and Van der Waals."
> (A1 chemistry student, assessment response, February, 1996.)

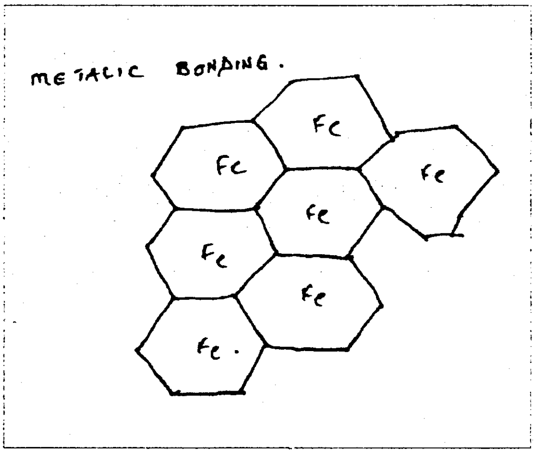
> "Copper:- has bonding of covalent character as it is a stable metal."
> (A level student, response in A level mock, March 1994.)

§A39.1.5: Carol.

In Carol's final interview she had suggested that the types of bonds she was familiar with were "covalent, dative and ionic" (C3.10). When she was asked if she knew about metallic bonds, she responded by asking "is that when you've got positive ions surrounded by a sea of electron kind of" (C3.12). Carol pointed out that "that's a bit different to covalent" (C3.14), apparently suggesting that in some sense it did not qualify as a proper bond. When asked if it *was* a bond, Carol agreed - although tentatively - that "it is, because they hold together, so there must be a bond somewhere" (C3.16).

§A39.1.6: Kabul.

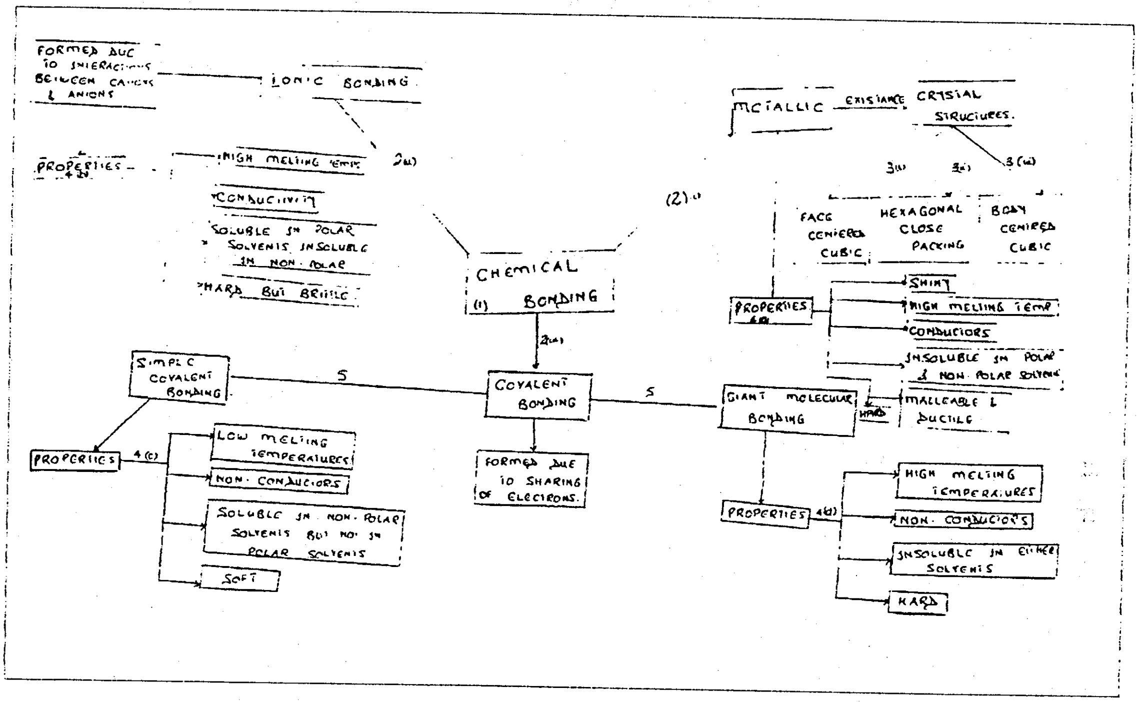
In Kabul's first interview, he had thought that "probably" the atoms in iron would "stick together" (K1.A378). He thought there must be some sort of force attracting the atoms together, but he had not "heard the name" (K1.A378). The bonding was "different" to covalent and ionic, and Kabul suggested that "it's probably metallic bonding", but he could only explain that this was "probably found in metals" as he had "just made that up" (K1.A389). He actually had "no idea" what this metallic bonding might be (K1.A395). Later in the term (18.11.92) when he was asked to draw representations of the type of bonding he knew of, Kabul included metallic bonding, although his diagram did not give any clear indication of what this type of bond was.



Kabul's representation of metallic bonding, November 1992

Kabul was asked about this diagram during the second interview. He explained that he had "just read-up it was a hexagon. Iron, iron forms a hexagon around it's shell, you know, metallic bonding" (K2.A456). Kabul appeared to have developed a hypothesis about the nature of the hexagon, that "iron has got, er, two electrons in this s-shell, and four [sic] electrons in its d-shell" (K2.A456). (I attempted to suggest to Kabul that there were *six d electrons* but he seemed unable to see this point, just agreeing "yeah, six electrons", and repeating "it has got six electrons, hasn't it", {K2.A456}). The lines of the hexagon meant "it has got six electrons in its outermost [sic] shell, which are bonded to other electrons of the metal" (K2.A474). Kabul was able to suggest how he would extend this formalism for other metals. The shape he would draw "depends on how many electrons does it have" (K2.A489). For zinc this would be "a decagon", for manganese a "pentagon", for chromium a "tetrahedral shape", for vanadium "probably a triangle", for titanium "just two lines", and for scandium "just a single line" (K2.A489). Kabul did not extend this approach to the s-block elements potassium and calcium where he would "just draw circles. With just a 'plus', and 'two-plus' in between" (K2.A499).

At the beginning of his fourth interview Kabul listed the bonding types he was familiar with, and he suggested "metallic bonding which occurs in ... metals" (K4.A056), but he was only able to add that "it's just bonding between metal atoms" and "it gives rise to ... close packing structures" (K4.A056). Later he was asked about focal figure 6, where he thought there was "metallic bonding" (K4.A542), and when asked what that was, 'exactly', he was again only prepared to suggest that "it's the bonding between metal atoms" (K4.A542). However Kabul had revised his notion of metallic valency, as he now thought each iron atom could bond to "twelve" others (K4.A546). He was also prepared to describe how the force between atoms was "the force from the nucleus. ... The nucleus of iron tends to attract electrons from the nucleus of other iron atom"s (K4.A549). At the end of the first year of his course Kabul produced a concept map for 'chemical bonding' as a revision exercise. Whereas the concept map he had produced in the previous September, at the start of the course (see appendix 37, §A37.1.1), showed two types of bonding (covalent and ionic), the new map included 'metallic' as one of three types of bond.



Kabul's concept map for chemical bonding, June 1993 (end of first year)

§A39.1.7: Umar.

In Umar's first interview he saw focal figure 6 as representing a "load of iron atoms" (U1.A388). He thought there would be bonding, and it might be metallic bonding, which he knew only occurs in metals, and involves a 'sea of electrons' to hold it together. However, Umar felt this was something that had been given little attention at G.C.S.E., and he had just learnt this from the syllabus when revising. In his second interview Umar reiterated that metallic bonding "only occurs in metals", but he thought "it's a bit difficult to put it into words" (U2.A392). He again said that in metallic bonding "a sea of electrons" forms (U2.A392), but he also suggested that "in metallic you've got positive ions and negative ions [sic], and like the positive attracts negative ions ... they're already charged ions, and they attract each other" (U2.A400).

In order to understand how Umar construed positive and negative ions to be present he was asked about an example of a metal, and he suggested tin. However it transpired that, despite his previous comments, Umar did not think there could be metallic bonding in a *pure* metal,

> "no it won't have any bonds in it, because it's just pure, ain't it? It will be just atoms, it won't be charged"
> U2.A414

However, Umar did think that something "attracts atoms together to form *molecules*" (U2.A425). Umar's conception of metallic molecules appeared to be related to an atom's covalency. That is, the number of atoms in a tin molecule "depends how many like electrons in the outer shell, how many bonds between each atom there are" (U2.A425). So Umar did think there would be bonds in a pure metal, although these would not be metallic bonds (U2.A425). Umar thought metallic bonds existed "between two metals" (U2.A443). So, for example, in an alloy between chromium and iron "it would be the ions that are bonded together" and "chromium might be ... negative, and iron be positive, so they'd attract each other" (U2.A443).

It would appear then that at this stage of his course Umar knew there was something in metals called a 'sea of electrons', but when asked about bonding in metals he described either a covalent case (molecules) in pure metal, or an ionic case in alloys. When he was interviewed near the end of his first year Umar gave even less detail, describing metallic bonding as "a bit like ionic I think, but it's only between metals" (U3.A042). However shortly after this Umar did use the 'sea of electrons' metaphor in both a revision exercise, and his end-of-year examination,

> "Metallic - between valence e^- of metallic atoms. ... Positive metal ions held together by *a sea of electrons*."
> (Concept map on chemical bonding, June 1993.)

> "Metals are good conductors of electricity and, when heated in a vacuum, will emit electrons. This can be explained by the delocalised [electrons] present in all metals. These act as *a sea of electrons* and attract positive metal ions together to form a lattice. The positive ions are prevented from repelling one another due to the shielding affect by *the sea of electrons*. ..."
> (End-of-year examination response, June 1993.)

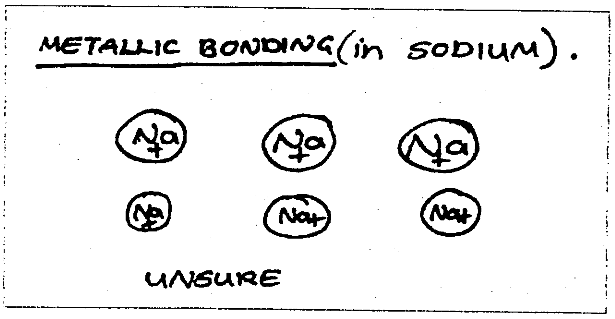
In these extracts Umar seems to be starting to think about metallic bonding in electrostatic terms, although he does not attempt to explain the notion of 'a sea of electrons' in any depth.

§A39.1.8: Noor, Paminder, Tajinder.

By the end of the first year of Noor's course she had acquired a model of metallic bonding, although this seemed to be based on an analogy with the more familiar ionic bond, rather than seen as an electrostatic interaction in its own right,

> "Metallic bonding *is like a special kind of electrostatic bonding* [where] the valence electrons in an atom swim free in the lattice of an [sic] metal, the +ve atoms [sic] and the -ve swimming delocalized electrons attract one another..."
> (Concept map on chemical bonding, June 1993.)

In the first term of Paminder's course she drew diagrams of the types of bonding she knew of, and one of her diagrams was meant to represent metallic bonding, although she added the legend "unsure",



Paminder's diagram of metallic bonding, November 1992.

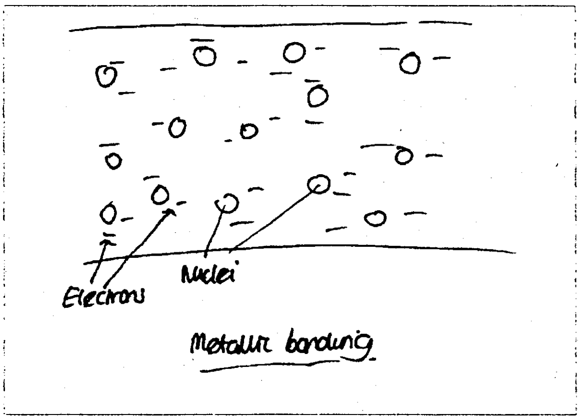
Paminder was asked about this diagram in the second interview, at which time she still seems to have difficulty making sense of a bond that is neither ionic nor covalent. She explained that metallic bonding was where the metals atoms were bonded between themselves, but her explanation did not go any deeper,

> "suppose you have, say for example, sodium, right? Sodium's like made up, suppose you have metal, a sheet of sodium metal, yeah, that consists of metallic bonding, that means like it's made of, like, the metal sodium, and it's just like bonded like between itself, *it's not ionic, and it's not covalent either, it's like, it's hard to explain this.* It's just like that metal's bonding there, I mean you don't have something like chlorine mixed with it, and, do you get me? {laughs}"
> P2.A195

In Tajinder's first interview, he knew there was a category of bond called 'metallic', but seemed uncertain of the detail of this type of bonding, beyond the presence of free electrons,

> "Metallic bonding ... I think they use it, in a railway, in a railway system, when they pass electric current, through the top, you know when they have the wires, like when the train passes, and they have like steel, I think, I'm not sure what it is, but like metal, and it's all like this [focal figure 6] but there's lots of like electrons, around, there's just free electrons roaming around, so that's why electric current can pass through, and that's ...[something] ... I think I got wrong before, when I said like 'electrons can't just go away by themselves', well I think they can."
> T1.B074

It would appear from this latter comment that for Tajinder the term ‘free electrons’ was taken quite literally, so that they were seen as “by themselves”, rather than having a role in bonding the structure together. At the end of the interview he reiterated that the metallic bond was “where there’s ... lots of nuclei, of a certain kind, like say for instance iron, and there’s electrons, which are free to move within a certain area, and this is metallic bonding” (T1.C208). Later in the term Tajinder was asked to draw diagrams representing the types of bond he was familiar with. His diagram for metallic bonding showed 14 circles (‘nuclei’) and 29 dashes (‘electrons’) sparsely arranged between two lines.



Tajinder’s figure of metallic bonding, November 1992.

In his second interview Tajinder described how, “electrons would be like in the metal itself, ... it would be able to move about in the lump of metal”, and he explained that an electron “wouldn’t just float off by itself, but it’s just there in the lump of metal” (T2.A168). He seemed unclear exactly *where* the electrons *could* move. Tajinder thought the electrons would “be moving constantly” in a lump of sodium, so he supposed “they would be able to move around”, although “it should be the same kind” of movement as an electron would have in a single atom, where “they have a certain area which they can move around in” (T2.A168). Tajinder seemed to be implying at this point that the electrons did not leave the atom, although he changed this after being asked for confirmation three times,

I: So it’s only within the atom they can move around is it?
T: Uh huh.
I: They have to stay in the atom and move around?
T: Yeah.
I: So in a sodium metal, or any metal I suppose, you’ve got electrons moving around,
T: Yeah.
I: but are they just moving around their own atom?
T: Erm, yeah, they’re moving around, ah no, I think they would be able to move around the whole block of the metal ... just the outermost one.

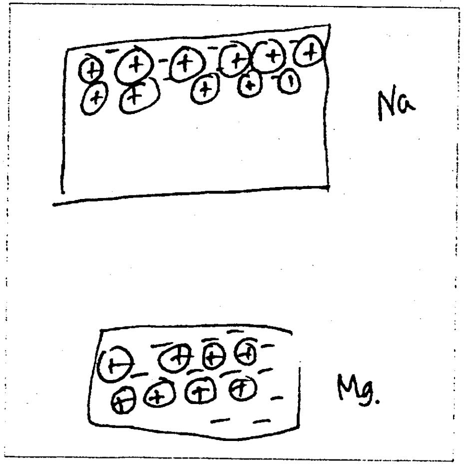
T2.A168

In his third interview Tajinder described the metallic bond as "an arrangement, like nuclei, and there's a sea of electrons around them", but explained that there was "the force of attraction-repulsion, attraction between, the lithium nuclei, and the surrounding electrons of other lithium nuclei ... [and] the repulsion of the lithium nuclei and another lithium nuclei" (T3.B039). However, Tajinder also referred to how in lithium metal the atoms would be constantly "giving ... away" or "passing ... around" the electron (T3.B131). Tajinder extended the 'sea' metaphor to have the conduction electrons 'floating',

> "when you have two electrons like that *floating* around you need more energy to ... give to the nuclei to attract its own electrons back, from the ones that are *floating* about the sea of electrons, ... they're *floating* around the outer electrons ... they'd be electrons like *floating* about ..." T3.B179

And a little later in the interview Tajinder described metallic bonding as "nuclei with a *sea* of electrons *floating* about" (T3.B249). In the fourth interview Tajinder again describes the metallic bonding in lithium in terms of "a lot of lithium nuclei surrounded by a *sea* of electrons which are which are free to move around the outer shell of each lithium atom" (T4.A207), and again the electrons were construed to be "*floating* around" (T4.A226).

When he was asked about the types of bonding he was familiar with near the end of the first year of his A level course, Tajinder drew two examples of metallic bonding, and as he explained what he was drawing he referred to both the "the attraction between the electrons and the positive ions" and "*the sea of electrons*":



Tajinder's figure of metallic bonding, June 1993.

> "metallic bonding takes place in metals, and this is where, say you have sodium, now sodium doesn't exist by itself [as] an atom 'cause it's not stable, and it's quite reactive. So it forms with other sodium atoms to form a type of solid. And this solid is where there's positive ions in the solid and the electron on outermost shell is like delocalised and it's free to move around the area, and only electrons in the outermost shell can take part in metallic bonding and what holds it together is the attraction between the electrons and the positive ions, between one another, that's what holds it together. Mm. If you have magnesium which has two outer electrons, then two electrons can become involved in *the sea*, in the solid, and they're called the, *the sea of electrons*, going moving around the positive ions, and that's why you can pass electric current through metal because the electrons are free to move through a metal so that's how they can pass on electric current."
> T8.A200

So Tajinder's vague knowledge of 'free' electrons at the start of his course appeared to have evolved into a type of bonding involving electrostatic interactions, but described in terms of electrons 'floating' in a 'sea'.

§A39.1.9: Incidental data.

In the 1994 College mock A level examination, of the 31 students answering the question on bonding, 23 (74%) referred to metallic bonding when explaining the bonding in copper, and an equal number mentioned the "sea" of electrons. Some students referred to the 'sea' of electrons without giving any clear indication of what this metaphor is meant to imply, being satisfied to provide simple descriptions,

> "Copper has metallic bonding, it has a sea of delocalized electrons present in it"
>
> "Copper is made due to metalic [sic} bonding (a lattice surrounded by a sea of free electrons)."
>
> "copper - this contains metallic bonding. It has a central positive atom with a sea of delocalised electrons."
>
> "Copper - is an arrangement of Copper ions arranged in a giant 'sea of electrons'."
>
> (Mock examination responses, March 1994.)

The following example is from a student who made the electrostatic nature of the bond explicit,

> "Copper is a metal and consists of metallic bonding in which *+ve* ions are *attracted* to sea of an electron cloud. - Copper atom will have *+ve* ions contained within it, this will be very strongly *attracted* to the sea of electron cloud."
> (Mock examination response, March 1994.)

However, a number of students (7) used a simile, that the sea of electrons acted *like glue*, rather than directly invoke electrostatic attractions. For example,

> "Copper is a metal. It has a metallic structure consisting of metallic bonding i.e positively charged ions in a 'sea' of electrons. In other words the electrons are not fixed in bonds but delocalised over the whole structure. (The electrons are thought of as glue, holding the structure together.)"
> (Mock examination response, March 1994.)

Some students clearly understood that the number of electrons in the 'sea' was related to the number metal ions present, for example,

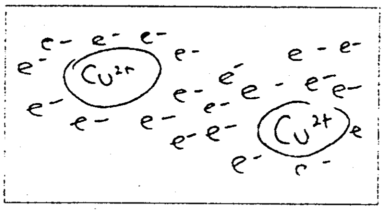
> "Each copper atom donates two electron to the sea of delocalised electrons which 'glue' the anions [sic] together very closely."
> (Mock examination response, March 1994.)

§A39.1.10: Incidental data.

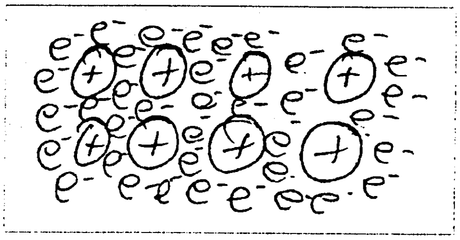
However, the following extract could be read to suggest an excess of electrons in the 'sea',

> "Copper is a typical transition metal & shows metallic bonding with the cations (Cu^{2+}) sitting in a sea of anions (electrons). The electrons act like glue & there [sic] *great number* means that there is very strong bonding."
> (Mock examination response, March 1994.)

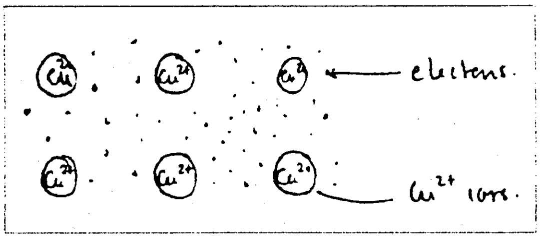
Certainly several of the students' diagrams of metallic bonding in copper seemed to show such an imbalance of charge, similar to Tajinder's (November 1992) diagram presented above (§A39.1.8),



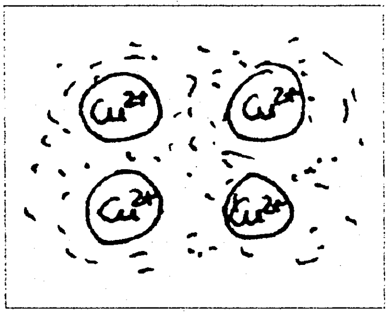
"Copper is held together by metallic bonding, where a central cation is surrounded by a sea of electrons"
(Mock examination response, March 1994.)



"Copper. This has mettalic [sic] bonding. In Mettalic bonding the atoms are held together in a "sea" of electrons which acts like a glue."
(Mock examination response, March 1994.)



"Copper forms metallic bonds, ie its ions are surrounded by a sea of electrons"
(Mock examination response, March 1994.)



"Copper is a metal. It has a metallic structure consisting of metallic bonding i.e positively charged ions in a 'sea' of electrons ..."
(Mock examination response, March 1994.)

§A39.1.11: Incidental data.

It was reported above that colearners might extend the 'sea' imagery so as to have electrons that 'floated' or 'swam' in the sea. Two of the students taking the examination extended the 'sea' metaphor to suggest that the cations were *like islands* in the sea,

> "Cu consists of islands of Cu^{2+} ions in a see [sic] of free/delocalised electrons"
>
> "Copper. metallic bonding. This is like a sea of electrons A positive charge being like an island surrounded by electrons."
>
> (Mock examination response, March 1994.)

Other examples of comments collected suggest that various aspects of the 'fluid' metaphor may be adopted by students,

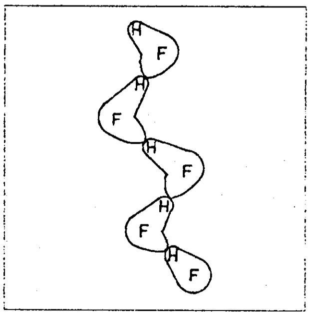
> "A 'sea of electrons' *drift* about in metallic bonds."
> (proposition from concept map on chemical bonding, second year A level student two weeks before final examination, May 1992.)
>
> "Metallic bonding is a type of bonding exhibited by metals. The +ve metal ions are *suspended* in a "sea" of dissociated "free" electrons"
> (proposition from concept map on chemical bonding, second year A level student two weeks before final examination, May 1992.)
>
> "Iron is a metal and shows metallic bonding within its structure. The Fe^{2+} and Fe^{3+} ions are located in the structure and are *floating* in a sea of delocalised electrons."
> (student explanation after 1 term of A level chemistry, January 1995.)

In the interview study there was some suggestion that the 'sea of electrons' description of the metallic bond - although limited in itself - could act as a suitable image for developing an electrostatic model of the bond. However, the evidence from the mock examination presented above suggests that even if these A level examination candidates had acquired an electrostatic model of the bond, a significant number were content to give examination responses in terms of the 'sea' image alone. This is an issue that is considered in chapter 12 (§12.4.3). The following proposition from a concept map (drawn up as an end-of-first-year revision exercise) suggests that even when an electrostatic model of the bond is taken up, this may supplement - rather than develop - the 'sea' metaphor,

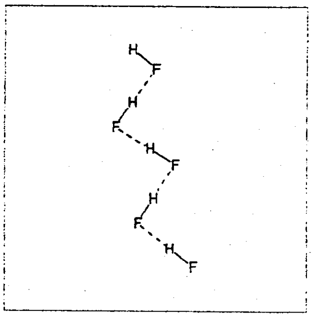
> "Metallic bonding is only occrent [sic] in metals and is the attraction between the +ve charge of the metal ions and the -ve charge of the electrons. It *also* has a sea of electrons which flow around the structure."
> (Concept map, first year student, June 1994.)

§A39.2: Learners' classifications of intermolecular bonds.

In chapter 11 (§11.6.) it is suggested that if learners commence A level with a bonding typology limited to covalent-ionic, then they do not have appropriate categories to deal with inter-molecular bonds.



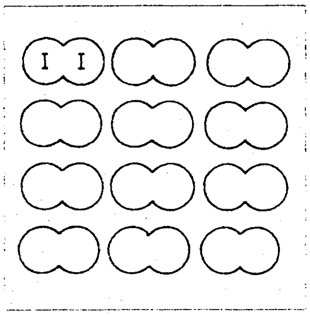
focal figure 11



focal figure 22

§A39.2.1: Annie, Jagdish, Mike, Tajinder, Kabul, Lovesh, Paminder, Quorat, Umar.

When Annie was shown focal figure 11 in her first interview she explained that there was bonding "within the sort of shape of the H-F, but when it meets up to like the H-F on the corners of the other shapes, they don't actually bond" (A1.426). Jagdish, when shown focal figure 22 in her first interview, thought there were single bonds in the molecules (J1.B100), but that the molecules were "not stuck together" (J1.B104). In Mike's first interview he suggested that in focal figure 11 "the molecules are attracting one another" (M1.B115), but he was "not sure about bonding though" (M1.B142), and in Tajinder's first interview he thought that the dashed line in focal figure 22 was "a force between them, it's not actually a bond, but it's a force" (T1.C037).



focal figure 17

When colearners were first shown focal figure 17 they often did not think there was any bonding between the molecules (Annie, A1.726; Jagdish, J1.B017; Kabul, K1.B256; Lovesh, L1.A497; Paminder, P1.B210; Quorat, Q1.B045; Tajinder, T1.B493 and Umar, U1.A468). To explain how solids were held together without chemical bonding colearners sometimes suggested that this was due not to chemical bonding, but rather just due to forces, and this notion that chemical bonding is perceived as something other than forces is considered below, in the final section of chapter 11 (§11.7).

§A39.2.2: Carol, Paminder, Debra, Kabul.

However, sometimes colearners did identify intermolecular bonding, but - as with the metallic case above - in terms of the familiar categories of covalent and ionic bonding. In Carol's first interview she had identified the intermolecular bond in hydrogen fluoride (focal figure 11) as "ionic" (C1.526), although she thought,

> "that don't make sense, really. Because, where ... it's, in the molecules there's hydrogen and fluorine, and where the molecule joins another molecule there's hydrogen and fluorine, and you can't say one has got covalent, and one has got another type of bond ... because it just doesn't make sense."
> C1.563-5

So Carol did not wish to accept that the two bonds between hydrogen and fluorine were different, but in classifying them she used the covalent-ionic dichotomy. In her second interview Carol used the term 'hydrogen bond', although her description of this type of bond as "the bond where ... one of the atoms, atoms, gets all ... the electrons and takes it completely away, from, the other atom" (C2.536), and which has "all its electrons [are] like kind of taken away ... by the other one" (C2.540), suggests that this is an ionic bond in all but name.

In her second interview Debra initially described the bonding in hydrogen fluoride (focal figure 11) as "polar bonding between the, hydrogen and the fluoride, and there's van der Waals forces between the hydrogen of the other molecule and the fluorine" (D2.337). However subsequently she changed her mind, and suggested that there was "hydrogen bonding between the hydrogen and fluorine, and then that's the ionic bond" (D2.341). Debra confirmed that it was the ***intermolecular*** bonding which was ionic (D2.349).

In Debra's first interview, she explained the nature of the forces between iodine molecules, but does not seem to have a suitable name for this. Debra knows the interaction is electrostatic in nature, and although she knows it does not show the characteristics of ionic bonding, she initially accepts this label. It is as if Debra feels all bonds should be called 'covalent' or 'ionic'. (One could conjecture that had the suggestion of 'ionic' been presented first, she may have rejected this option, and accepted 'covalent'.)

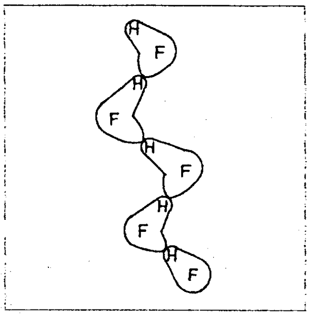
D: Yeah there's bonding between the iodine molecules themselves.
I: What kind of bonding is that?
D: Erm,
• • • • [pause, c.4s]
D: electrostatic.
I: Electrostatic?
D: Yeah.
I: Why should there be an attraction between these iodine molecules, are they charged?
D: No, there's an attraction between the electrons of one, and the nucleus of another. Erm.
• • • •
I: So the nuclei from this molecule, attract the electrons from this molecule? Is that what you're saying?
D: Yeah.
I: And vice versa?
D: Yeah.
I: Any idea what we might call that type of bonding?
D: Can't remem-
I: Is it a covalent bond?
D: No.
I: Ionic?
D: Yes.
I: It's an ionic bond, is it? So you think iodine molecules are ionically bonded together?
D: No.
I: No. Are there any ions present?
D: No.
D1.835

In Paminder's first interview for the research she suggested that there were "*nine*" bonds in "hydrogen fluoride" (focal figure 22), and that these were "ionic" (P1.B238). Paminder did not distinguish between the polar bonds and the hydrogen bonds, although in her interpretation both hydrogen and fluorine were demonstrating unusual valencies.

When Kabul first saw focal figure 17 he identified covalent bonds between iodine atoms, but no other types of bonding (K1.A449). He knew that the molecules in iodine "stay stuck together", but could not suggest what kind of force might be responsible for this (K1.A471). Later in the interview the figure was revisited, and Kabul again identified covalent bonding (K1.B253), and counted "twelve" covalent bonds in the whole figure (K1.B256). The diagram showed that "the molecules have been separated", and so there was no bonding between molecules, and they would not stick together (K1.B256). However, in real iodine (rather than the diagram) the molecules stay together, because there would be bonding between them. Kabul thought that this would be "covalent" bonding, which would extend in all different directions (K1.B265). So, despite the figure, Kabul assumed the integrity of solid iodine was due to a giant covalent lattice.

§A39.2.3: Debra, Paminder, Umar.

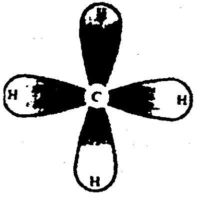
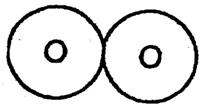
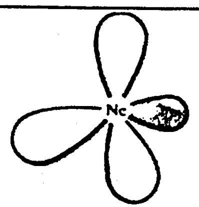
Although colearners were generally unaware of hydrogen bonding at the start of their A level courses, there were a number of examples in the interviews of the *term* 'hydrogen bond' having been acquired, without an appreciation of the intended meaning.



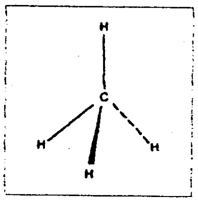
focal figure 11

In her second interview Debra suggested that there was "hydrogen bonding between the hydrogen and fluorine, and then that's the ionic bond" (D2.341). Debra confirmed that she meant that the *intramolecular bonding* was hydrogen bonding (D2.343).

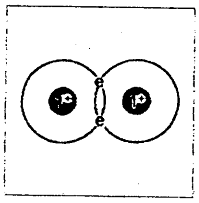
Similarly, in Paminder's first term she undertook Kelly's construct repertory test, and she used a construct "hydrogen bonding present" to discriminate elements in one triad presented to her. However, Paminder's construing of the triad elements did not follow the CURRICULUM SCIENCE use of the term hydrogen bonding, as is demonstrated in the following table,

construct	 triad element 243	 triad element 245	 triad element 424
hydrogen bonding present	✓	✓	✗

Two other figures construed as having "hydrogen bonding present" were triad elements 221 and 314, neither of which would be so construed from the CURRICULUM SCIENCE perspective,



triad element 221



triad element 314

In Paminder's second interview she was asked about her meaning of the term 'hydrogen bonding'. She responded giving as an example the bond within the hydrogen molecule,

> "say for example hydrogen gas, that consists of two atoms of hydrogen, and when they bond they, each one has one electron in its outermost shell, and when they bond, they bond like covalently. And that's what hydrogen bonding is. That's an example of hydrogen bonding."
> P2.A278

When she was asked for another example Paminder referred to her concurrent work in biology where she was studying DNA,

> "at the moment we're doing like about DNA and double helixes, and DNA consists of like bases, of three things actually, ... But they've got bases, and they're joined by hydrogen bonding. But the hydrogen bonds are actually holding two <u>bases</u> together."
> P2.A283

This was an appropriate example of hydrogen bonding from within CURRICULUM SCIENCE, but did not actually explain what the bond was. When Paminder was probed further her explanation of the hydrogen bond remained vague,

> I: So what is a hydrogen bond?
> P: A hydrogen bond is
> •
> P: what I just told you.
> I: A hydrogen bond is what you find holding the bases together at the centre of the strands of D.N.A.?
> P: Yeah. It's like the hydrogen is bonding to two other things and keeping them together, that's *another* example.
> I: That's another example?
> P: Yeah.
> I: But also in hydrogen you have a hydrogen bond?
> P: When you have two hydrogen atoms, yeah.
> I: In a molecule?
> P: Yeah.
> I: And that's a different example is it?
> • • •
> P: In a sense yes, in a sense no, because like it's still the hydrogen that is being bonded to something else.
> P2.A295

Paminder was asked about methane, which she had previously construed as having "hydrogen bonding present". Paminder explained that in methane there was hydrogen bonding "to the carbon atom",

> I: Er, is there any hydrogen bonding in methane, CH_4?
> P: There is to the carbon atom, but not, well, not between hydrogen and hydrogen.
> I: So there's hydrogen bonding between what and what exactly?
> P: You know CH_4 is methane, yeah?
> I: Mm.
> P: You have carbon atom, which is joined covalently to four individual hydrogen atoms. The hydrogen hydrogen atoms aren't joined, but the carbon and hydro¬, the carbon is joined to each hydrogen atom.
> I: And that's hydrogen bonding?
> P: Yeah. Think so.
> P2.A302

Paminder thought this was an example of hydrogen bonding, "because, if you think about it, you know, 'hydrogen bonding', that's like, you know, 'what is *hydrogen bonding* to?' It's kind of that sense" (P2.A309). Paminder had apparently met the term hydrogen bond, for example in biology, and seemed to have just adopted what seemed a likely meaning, i.e. a bond to hydrogen.

Similarly, Umar seemed to have made the same 'intelligent guess' at what was meant by the term,

I: Do you think any of the following things contain hydrogen bonds? A neon atom?
• [pause, c.1s]
U: No.
I: Erm. A hydrogen chloride molecule?
• • • •
U: Yeah.
I: A methane molecule?
U: Yeah.
I: How many hydrogen bonds do you think there will be in a methane molecule?
U: Four.
I: How many in a hydrogen chloride molecule?
•
U: One.
I: Do you know what a hydrogen bond is?
• • •
U: Not really, but like, I'm thinking of it like, if it's if hydrogen's bonded to another atom.

U2.B034

Appendix 40.

Evidence of octet thinking: the 'just forces' conjecture.

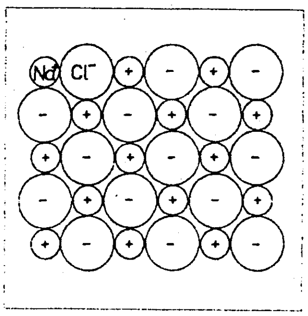
§A40.0: The role of this appendix.

In chapter 6 of the thesis a model was presented to describe the main aspects of A level students' developing understanding of chemical bonding, as found in the research. Chapter 11 develops one of the main themes introduced in chapter 6, i.e. that learners exhibit *octet thinking*.

It was explained in the chapters on the methodology employed that the model developed is *grounded theory* (§4.4), and as such its authenticity needs to be demonstrated in terms of the data from which it *emerged* (§4.2.5 and §4.4.5). This appendix provides more detailed evidence to support the contentions presented in chapter 11, section §11.7.

§A40.1: Ionic bonds as just forces.

In chapter 11 (§11.7.1) it is suggested that colearners distinguished between interactions between ions that were ionic bonds and those that were just forces.



focal figure 5

§A40.1.1: Jagdish, Kabul, Paminder, Tajinder, Lovesh.

In Jagdish's first interview she thought that each sodium ion in sodium chloride had an "*attraction* to all six, chlorine ions" that were nearest neighbours (J1.A215), although it could only be "joined" to one of them at any one time (J1.A190).

In Kabul's first interview he suggested that in the NaCl lattice (as represented in focal figure 5), each ion was ionically *bonded* to one other (K1, 24.9.92). He was asked about forces, and he thought there was "attraction force" between the sodium ion and the chloride ion it was bonded to, although he could not suggest what kind of force it might be (K1.A295). He thought there would "probably" also be forces between an ion and the other counter ions around it, but the greatest amount of force was with what he described as "the *one* to which it has been attracted" (K1.A295). The force was stronger because "it has given its electron to that one", and this "makes the sort of attraction" (K1.A309). A force would have to be applied to separate the ions, and the most force was needed to separate an ion from "the *one* to which it has been attracted" (K1.A340). It would seem that Kabul saw an ion as *attracted* to one other (the ion it was *bonded* to), although there might also be *forces* with other ions. The terms 'force' and 'attraction' appear to be given different meanings here.

In his second interview Kabul discussed the ionic bond in sodium chloride in terms of electron transfer between a sodium atom and a chloride atom, but suggested that "there should be some forces holding the... the ions together", otherwise "just sodium and chloride ion would just, you know, fall apart" (K2.A314). Kabul seemed to be suggesting that ion pairs would break away from the crystal. They did not just drop off, and so "there should be some *intermolecular* forces between them" (K2.A322), or rather - as there were no molecules present - "probably inter-crystal [sic] forces" (K2.A322) "between the ions" (K2.A369). Kabul maintained this general view in his third interview, distinguishing between strong forces where electron transfer had occurred and weak forces between other pairs of ions,

I: What you appear to be saying is that the idea of bonding between two ions,
K: Yeah.
I: and the idea of ion formation,
K: Yeah.
I: by transfer of electrons, are intimately tied together.
K: Yeah.
I: And if I was to take a positively charged ion and a negatively charged ion,
K: Yeah.
I: that were already ionised, and just placed them next to each other, they wouldn't form a bond?
K: I don't think so.
I: Would there be any kind of interaction between them?
K: Probably weak, weak attraction.
I: And between ones where electrons have been transferred?
K: There will be a strong attraction.
K3.A131

In Paminder's first interview for the research she thought that in focal figure 5, a chloride ion would have formed a bond with "one" sodium ion (P1.A468). She distinguished the ionic bond from other cation-anion interactions, where because "that's positive and that's negative so they could have like a ***weak attraction***" (P1.A468). Paminder suggested that the ionic bonds "would be stronger because that's actually where the electron has been transferred" (P1.A468). For Paminder, the other interactions were not ionic bonds, but "***just a weak attraction***" due to "the positive charge on the sodium, and the negative charge on the chlorine. 'Cause as we know positive and negative attract" (P1.A468). When Paminder was interviewed again near the end of the academic year she had retained the distinction between the two types of anion-cation interaction in the sodium chloride lattice. There would be a force between any pair of adjacent ions, but something extra where electron transfer had occurred "because that's a positive charge and that's a negative charge and they're attracting, ***and plus*** if they have formed the bond, the positive has just donated one to the negative to make it negative, so they'll be a bond between those two, and so like there would be an attraction" (P3.A468).

Paminder explained that a cation in the structure "<u>is</u> attracted to the others, but I mean it only forms a bond with one of them" (P3.A474), and it is most strongly attracted to "the one it forms a bond with" (P3.A479), because "that's where it's transferred the electrons" (P3.A481). It was put to Paminder that there might be an equal force, but she thought "there can't be" (P3.A490). She explained that in the real sodium chloride structure, "first of all it will be three-dimensional, secondly, the chlorine that sodium has donated it's electron to, it will be slightly closer to that one" (P3.A493), so "maybe they're ***weak attractions*** which are ***like***, they ***act as*** weak bonds between the sodium and the chlorine, but the one it actually forms the bond which ***is*** the ionic bond" (P3.A498). Similarly, one of the negative ions would attract all the positive around it "slightly, but maybe one more than the other, which it forms a bond with" (P3.A503).

In Tajinder's first interview, he explained that although the ions in sodium chloride only formed one bond each, there were also other types of interaction, so "one chlorine is ***only bonded to one*** sodium, because a sodium, atom can only lose one electron, ... but, it, the thing is holding itself together because there's positive and negative charges, together" (T1.A446).

In Lovesh's first interview for the research his interpretation of the bonding in sodium chloride, as represented in focal figure 5, was similar to that of Jagdish, Kabul, Paminder and Tajinder, save for Lovesh mistaking the valency of sodium for two. He suggested that a sodium would be "bonded to chlorine", but to only two of the ions "because sodium donates two electrons to two chlorine" (L1.A314). He thought that although the sodium is only *bonded* to two chloride ions, it would be *attracted* to others "because they're negative, all the chlorines are negatively charged, they're attracted to the sodium which is positively charged. So that's why they're all attracted to each other" (L1.A314).

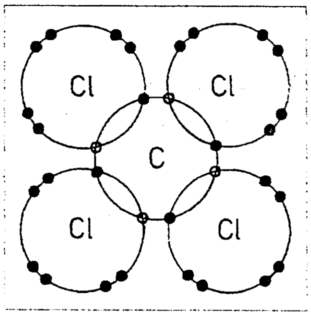
§A40.1.2: Incidental data.

Similar views to those elicited from these colearners have been expressed in responses to course tests undertaken by other A level students. In each of the following extracts there is an assumption of intramolecular ionic bonds, and weaker intermolecular interactions,

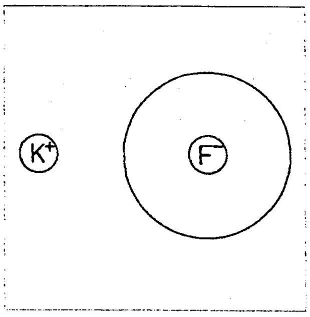
> "The bonding present between NaCl is ionic but from molecule to molecule weak V.D.W forces"
> "NaCl: is moleculary bonded ionicaly - it latice is held together by vand a Waals' forces"
> "The bonds between the ions are ionic. But between the ions there are van der waal's forces."
> (Responses to a first year assessment, February, 1996.)
>
> "Sodium Chloride is made up of ionic bonds between single Na-Cl atoms but van der Waals' bonding between adjacent molecules"
> (Mock examination response, March 1994.)

§A40.1.3: Annie, Carol, Kabul, Debra, Lovesh, Mike, Quorat.

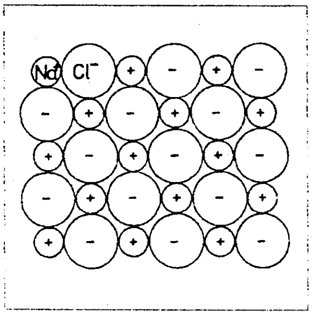
At certain points during the research interviews, the ionic category of bond was itself excluded from chemical bonding by some colearners. In some cases, such as Kabul and Lovesh (see below), this seems to be an alternative position taken up when the colearner was no longer able to accept the JUST FORCES CONJECTURE However, in some cases this view was adopted early in the interviews, rather than as a 'fall-back' position.



focal figure 3



focal figure 9



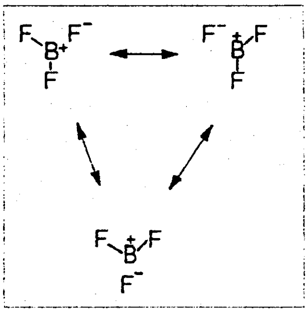
focal figure 5

For Annie, at the start of her course, bonding was represented "by the circles that overlap" (A1.134) in diagrams such as focal figure 3, so that she thought that in focal figure 9 there was no bonding "because they're not combined" (A1.354). In her first interview Annie did not think there was bonding in focal figure 5 (A1.283) where "they don't actually overlap or anything" (A1.242), but "it would probably get held together by *just forces*" (A1.256). This view was repeated in her third interview at the end of her course, when she said that focal figure 5 "hasn't got any bonding in it" (A3.30), rather "it's sort of attraction between the charges, so it would probably be held together by sort of van der Waals' forces" (A3.56). Later Annie said "there's no bonding present, but there is attraction" (A3.105). For Annie, sodium chloride crystals (the substance - rather than figure 5) comprise of "sodium and chlorine atoms joined to form the sodium chloride molecule" (A3.120) "by van der Waals' forces" (A3.122).

In Carol's second interview she suggested that where the bond*ing* was "ionic" the *forces* involved were "van der Waals' forces" (C2.151-3). Indeed if she considered two adjacent ions, they would "***not bond,*** but go together 'cause they're opposite charges" (C2.303). At this point Carol perceived bonds as *more than just forces*. It is interesting that for Carol it appears that 'bonding' did not necessarily imply 'bonds'. Perhaps she construed ionic bonding in a similar way to Kabul, who during his final interview, during the last term of his course, explained ionic bonding in terms of electron transfer, but at one point suggested "there's no bond" (K6.A390),

I: This is diagram number 5. Have you any idea what number 5 represents?
K: Erm, ionic bonding.
I: And is that different to covalent bonds?
K: Yeah.
I: So what's *ionic bonding?*
K: One of the atoms loses the electrons, another atom accepts the electrons, different atoms you know. So, *there's no bond*, there's no electron sharing.
I: No electron sharing. No bond?
K: There is a bond.
I: There is one, whereabouts is the bond?
K: Like between here, sodium ion it's between chlorine, this chlorine, it's between everywhere.
I: Between everywhere?
K: Yeah.
K6.A390

It is as if at some level Kabul did not construe the tenuous ionic bond, that was "between everywhere", as being *as much of a bond* as the covalent bond where there was "electron sharing".



focal figure 14

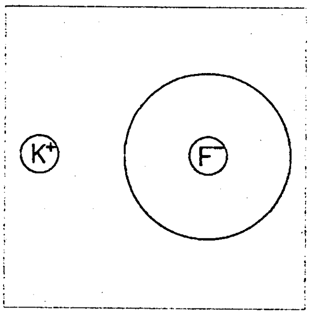
In Debra's second interview, she thought that each of the resonance structures in focal figure 14 showed "two" bonds (D2.879, 883, 885). However Debra thought that there was no bond between the BF_2^+ ion and the F^- ion (D2.895), although there was an attraction (D2.897). Despite the ions being shown adjacent, she thought that "there's no bond shown on the diagram" (D2.909).

When Lovesh considered focal figure 5 in his third interview, near the end of the first year of his course, he recognised ionic bond*ing* (L3.A407), although he no longer distinguished between different anion-cation interactions (as in the first interview, see above, §A40.1.1). However, Lovesh seemed reluctant to identify *any* ionic bonds, and instead described all the interactions as "attractions",

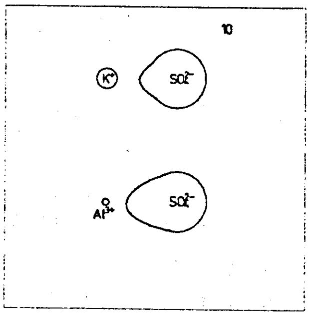
I: Is there a bond between those two species?
L: There's an attraction between
• (pause, c.1s)
I: Uh huh?
L: the cations and the anions.
I: Is that a bond, do you think?
•
I: Or would you not call it a bond?
•••••••
L: Hm.
••••
L: It's really an attraction between them, I think.
L3.A411

Lovesh now said he did not know whether there were any ionic bonds in the diagram (L3.A428). Indeed he was unsure of the existence of ionic bonds per se, so again the presence of ***bonding*** did not seem to imply the presence of ***bonds***,

I: Is there such a thing as ionic bonding?
L: Yes.
I: Is there such a thing as ionic bonds?
• • • [pause, c.3s]
L: I don't know.
L3.A428



focal figure 9

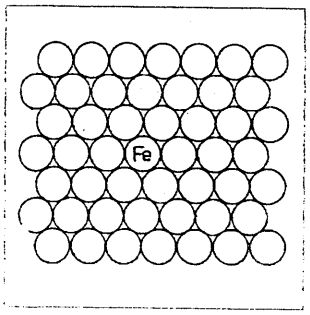


focal figure 10

Mike distinguished between bonds and attractions in several of the focal figures he was shown in the first interview he gave for the research. So in focal figure 9 the potassium and fluoride ions were "attracted, but they are not actually bonded in any way" (M1.B013). Similarly in focal figure 10 he thought "there's none [chemical bonding] being shown", although "there is an attraction, as the SO molecule [sic] has an attraction ... due to the difference in charges" (M1.B073). Similarly, in her first interview, Quorat thought that a sodium ion in focal figure 5 was "*not bonded*, it's *just attracted*" to "the chlorines" (Q1.A454).

§A40.2: Metallic bonds as just forces.

In chapter 11 (§11.7.2) it is suggested that some colearners did not consider that metals contained bonds as such, but rather *just forces* holding them together.



focal figure 6

§A40.2.1: Jagdish, Noor, Quorat.

In her first interview Jagdish did not think there could be any bonding in iron although the atoms "do stick together, otherwise you wouldn't be able to see iron" (J1.A326), so "there must be" force between the iron atoms (J1.A366). When Jagdish was subsequently asked if there was any bonding in the iron she responded "no, but there is a *force*" (J1.A470). In her second interview Jagdish did suggest that there was "metallic bonding between the atoms" in a metal (such as in iron retort stand that happened to be a convenient prop in the interview setting), but then changed her mind: it was "not metallic bonding between the atoms ... it's the way the atoms have been packed in the structure" (J2.A330). Although there was no bonding, there would be forces, and these would depend on the packing arrangement,

> "the one where ... fit spheres on top of spheres [*i.e.* body centred], ... you'd have weaker forces. ... Because it will be unstable, because ... you're not at the lowest energy level as possible ... Because if you fill in the spaces [*i.e.* close packing] you're at a low, lower energy level. But if you try and get on top of one another, you're not on the, you're not on your lowest energy."
> J2.A384

Jagdish went on to explain that "if they were just on top of each other, they wouldn't be as closely packed as if they filled in the spaces" (J2.A415), and,

> "if they're more close together, then they'll be more attraction between them ... Because ... it's like Coulomb's law ain't it? You've got less distance between two things ... you must have *some sort of force* acting between the atoms to keep them together, right? If they're closer together, then that force is going to be stronger. But the further they are, then the ... force will weaken, so, ... you're going to need less energy to ... melt it."
> J2.A418

Here Jagdish refers to forces and energy levels (although she is not sure what form of energy is involved, J2.A409), even though she does not consider this an example of chemical bonding. She is unsure about the nature of the forces acting, except that "you've got erm van der Waals' forces acting on it *as well*", and these are "intermolecular forces" that "act on non-polar substances" according to books she had read (J2.A428). When Jagdish is asked directly whether there is any chemical bonding in a metal she is unsure of an answer, but "it's not van der Waals' forces" (J2.A436). She was "still not sure about what metallic bonding is" (J2.A452). Jagdish thought she could "understand metallic bonding ... if you have two ***different*** liquid metals [i.e. such as chromium and iron], and you put then into same container" (J2.A452), but not "what bonding is holding the iron atoms together, into that structure", although she would "bet it's the same thing if I just had like two different containers of iron and melted together, and put them together into one container" (J2.A473). She admitted that found metallic bonding "a bit confusing" (J2.A465), and thought that "the books just drift over it" (J2.A473).

She explained the reference to *two* metals in the following terms:

> "You will have broken the bonding between the molecules [sic] in the chromium and the molecules in the iron, because you've melted it, so you know, you've broken those like bonding, you'd have separated the atoms there. But where they start to resolidify, because the temperature has gone down, hasn't it? You just left them to cool, because the atoms will have mixed, the chromium and the iron will have intermixed, they will just start bonding with each other, wouldn't they?"
> J2.A458

This will be "metallic bonding" and Jagdish claims she "can understand it then" (J2.A458). There is little evidence here why Jagdish is more comfortable with the bonding between different metals, than within a pure metal - she refers to the bonds before and after mixing, and without giving any details in either case. Jagdish's reference to molecules might give a clue to how she conceptualised the bonding, but she thought that "you can't just say one molecule of iron is so-many atoms" (J2.A465). She seemed to find the term 'molecule' a useful device for explaining - or giving the impression of explaining - bonding in metals, but it ceased to be useful when she had to explain what she meant *by* the molecule in a metal. In her own words, she found the term molecule "helpful when you say, when you talk about, *what are bondings* inside the iron that are holding it together, but not like ... *what is an iron molecule*" (J2.A473). Later in the interview Jagdish reiterated her position on metallic bonding when considering the bonding in magnesium, which was "metallic again, ... but I don't know what it is" (J2.B353).

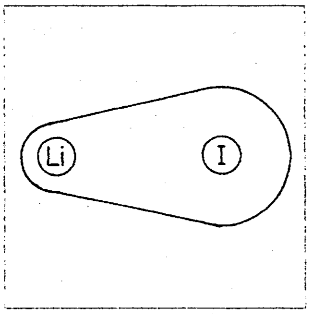
In Noor's first interview for the research she described focal figure 6 as "an arrangement of atoms, iron atoms" (N1.A427). She did not think there were any bonds present, and although there was an attraction, she thought "it's not a very strong attraction ... It's a very weak one" (N1.A427). Later in the term Noor drew diagrams representing the forms of bonding she knew about. Although she had heard of metallic bonding by this time, she was not sure how to draw it. She was asked about this in the second interview where she explained that she thought metallic bonding was "a bonding between two [sic] metals", that involved "positive and negative charges which attract each other", and was "a bit like electrostatic bonding" (N2.A161). Noor explained that "there's forces which hold the atoms together, called van der Waals' forces, and that's what holds like a lattice or something together" (N2.A161). So for Noor, although metallic bonding was "a bonding", she identified it with van der Waals' forces.

Quorat described metallic bonding in electrostatic terms in a test at the end of her first term, but considered this type of bond as "just a loose association", and she compared this with ionic and covalent bonding, which she described in terms of losing, gaining or sharing electrons,

> "The metallic bond is the bond formed between metal ions themselves. Metal atoms, sometimes have free electrons in their conduction bands that are free and have enough energy to leave the metal atoms. These leave the metal atoms, i.e. they become ions. These ions, are then positively charged, because they have lost electrons. Therefore the positively charged ions, are attracted to the electrons, therefore the metal forms this kind of lattice solid, with their own electrons that they have lost. This is called the metallic bond. Ionic and covalent bonds, are formed with other atoms or groups of different atoms, where atoms lose or gain electrons, or share them, where as [sic] metallic bonding is not the sharing or loss or gain of electrons. It is *just* a lose association with metal ions, and electrons they have lost, where this helps to hold the solid metal lattice together."
> (Test response, December 1992.)

§A40.3: Polar bonds as just forces.

In chapter 11 (§11.7.3) it is suggested that there were examples of colearners excluding polar bonds from full bonding status.



focal figure 8

§A40.3.1: Annie, Carol.

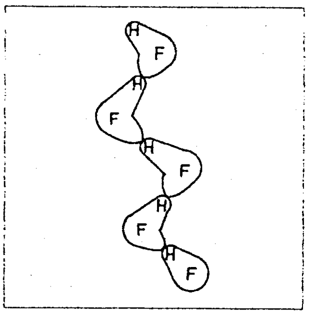
One example of this occurred when in her second interview Annie judged the forces between the atoms in focal figure 8 to be van der Waals, although as Annie described this as ionic and not polar, this may be considered consistent with her comments about the bonds in focal figure 5 during her first interview (above, §A40.1.3).

I: What type of bonding is that then?
A: Ionic.
I: That's ionic bonding?
A: Yes.
I: Okay, ... what kind of force holds it together then? What kind of force would you say holds it together, stops it actually falling apart so the lithium atom falls off one end, and the iodine off the other end?
• • • • • [pause, c.5s]
A: It's ionically bonded, but the forces holding it together will be,
• • • • •
A: van der Waals' I suppose?
A2.120

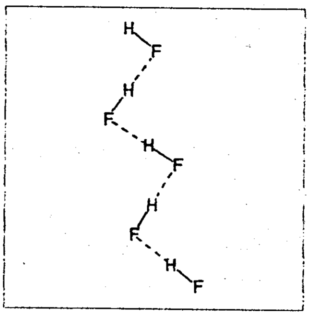
Carol presented an example where the polarity of the bond itself seemed to present the difficulty. During the second interview she was reluctant to classify the interactions in a hydrogen fluoride molecule as a bond. Carol did not "know whether they're actually ionic, or covalent bonds, I think it's like a force between them, because, the difference in electronegativity" (C2.410). She reiterated that the bond was not covalent (C2.422) or ionic (C2.426), but rather "something to do with electronegativity" (C2.428).

§A40.4: Hydrogen bonds as just forces.

In chapter 11 (§11.7.5) it is suggested that hydrogen bonding was prone to be being excluded as a type of bonding by colearners operating with the FULL SHELLS EXPLANATORY PRINCIPLE.



focal figure 11



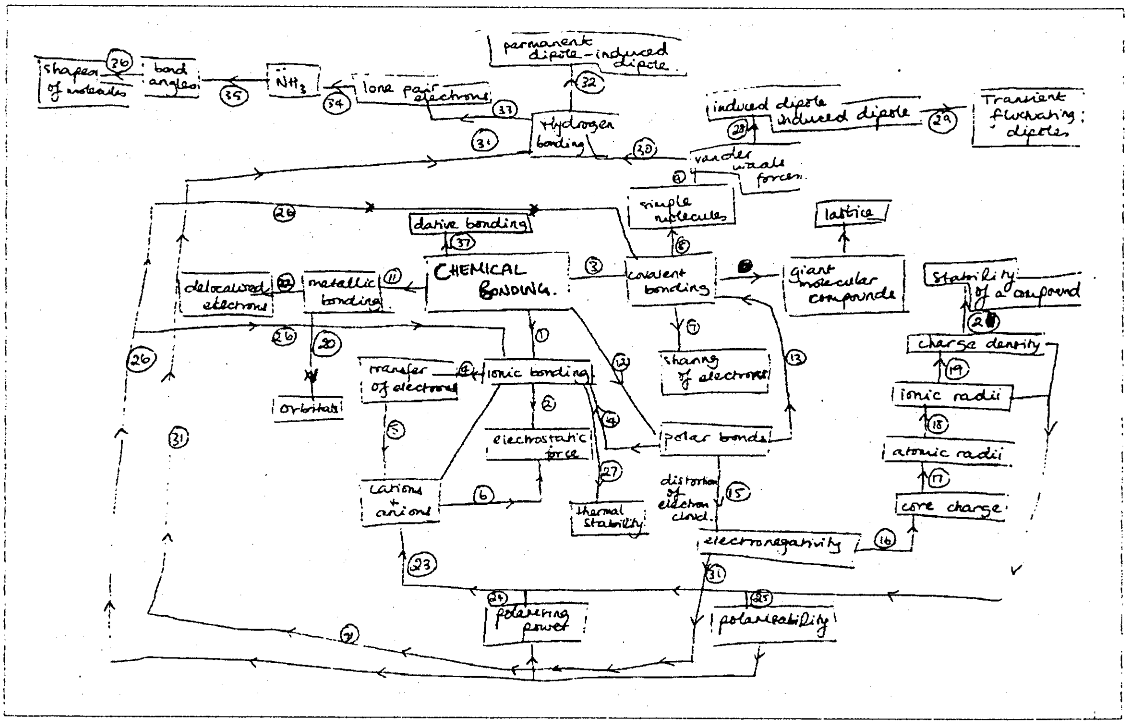
focal figure 22

§A40.4.1: Annie, Jagdish, Lovesh, Mike, Tajinder.

In her first interview Annie recognised that focal figure 11 showed a "chain of, hydrogen fluoride molecules" (A1.424), and she recognised bonding within each molecule, but when it meets up to like the H-F on the corners of the other shapes, *they don't actually bond.*" (A1.426). In her second interview she recognised that there was a "hydrogen bond" shown in focal figure 11 (A2.266) "between the, the H and the F of the like neighbouring molecule", but this would be "a lot weaker, than" what she referred to as "the *proper bond* of H-F" (A2.268). In a subsequent interview Annie she referred to how hydrogen bonding was "involved in just like basically holding molecules near each other" (A3.84).

At the time of Jagdish's first interview she did not seem to be aware of the existence of hydrogen bonds. In focal figure 22 broken lines were used to represent hydrogen bonds between HF molecules, but Jagdish suggested that a dashed line "just means that they're together, those two molecules are together"

(J1.B104), although "they're not stuck together" (J1.B104). She thought the molecules were attracted, that there was a force between them, but Jagdish did not know what kind of force it might be (J1.B104). In a concept map on 'chemical bonding' undertaken as an end-of-first-year revision exercise, Jagdish includes hydrogen bonding, but it is not directly connected to the central concept of 'chemical bonding' on the map, and it is described as "another type of intermolecular force".



Jagdish's concept map for Chemical Bonding, June, 1993.

In an interview near the end of the first year of his course Lovesh was asked to list the types of bond he knew of. He classed intermolecular interactions separately as "attractions",

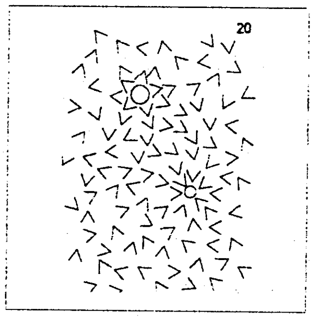
> I: Okay, so you've mentioned that there's various types of bonding, I think covalent, ionic, metallic, dative and polar you've mentioned, were there any other types?
>
> L: There are attractions, like intermolecular attractions, like van der Waals' forces and hydrogen bonding.
>
> L3.A105

Mike thought "there is an attraction" between the molecules of hydrogen fluoride in focal figure 11, although he was not sure if there was any bonding (M1.B142). In focal figure 26 Mike thought "there appears to be attraction between the electrons [of one iodine molecule] and other molecules" (M1.B427). Mike recognised the presence of "some attraction", but he would not call this bonding as "they're not joined together" (M1.B427).

In Tajinder's first interview he described the dashed line between two molecules in focal figure 22 as "a force between them, it's ***not actually a bond***, but it's a force. ... ***Not actually a bond***, but it's a force" (T1.C037).

§A40.5: Solvent-solute bonds as just forces.

In chapter 11 (§11.7.6) it is suggested that colearners would not consider solvent-solute interactions as bonds, rather they were perceived as just an attraction.



focal figure 20

§A40.5.1: Kabul, Lovesh.

Kabul thought focal figure 20 looked like the "process of solvation", and explained the attractions involved,

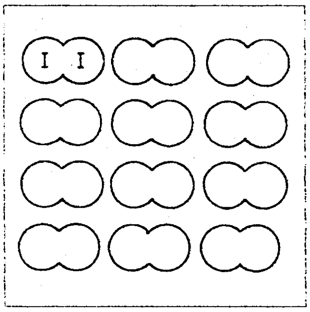
> "Looks like process of solvation, with ... it's like they're two atoms [sic], you can say in a crystal lattice, you know, one is positive and the other is negative, and these double arrows, the V shape, represents water molecules, with the pointed one being oxygen and those at the sides being hydrogen, and this represents that ... the smaller atom has got a plus charge which attracts oxygen atoms towards itself. ... The bigger atom has got minus charge so it tends to attract hydrogen atoms towards itself from water, and then the - the atoms become hydrated." K6.B250

Kabul thought that there were "loads" of bonds in the figure, "between the bigger atom and the smaller atom, between hydrogen and oxygen in water" (K6.B266). Kabul thought the bonds between the two "atoms" were "ionic" (K6.B266), and those between the hydrogen and the oxygen in water were covalent, but apart from this there were "no bonds" (K6.B270). When he was asked about hydrogen bonding, and reminded about the hydrogen and oxygen in water he added that "definitely, yeah, there is some hydrogen bonding" (K6.B273). However when Kabul was specifically asked whether there was bonding between the ions and the water molecules, he thought "no" (K6.B279). The interactions involved in solvating the ions were *not* considered as 'bonds'.

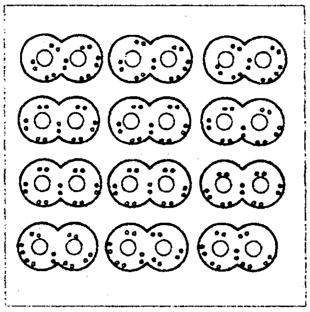
In the final interview with Lovesh, near the end of his course, he explained the solubility of salt as because "the lattice energy is smaller than the hydration energy and so it dissolves and you get aqueous ions" (L4.A275). Lovesh explained that "the hydration energy is the energy given out when an ion is surrounded by water molecules", and that energy would be given out "because it's *like a bond* being formed and so it's an exothermic process" (L4.A292). When Lovesh was was asked about the type of bond formed, he thought that "it's *just an attraction* really" (L4.A292).

§A40.6: Van der Waals bonds as just forces.

In chapter 11 (§11.7.7) it is suggested that van der Waals forces may not be considered as bonds where learners define bonds in terms of the FULL SHELLS EXPLANATORY PRINCIPLE.



focal figure 17



focal figure 26

§A40.6.1: Annie, Carol, Jagdish, Kabul, Lovesh, Umar, Mike, Tajinder.

Like hydrogen bonds, van der Waals forces do not involve the formation of octets, and thus may not be considered as bonds where learners define bonds in terms of the FULL SHELLS EXPLANATORY PRINCIPLE.

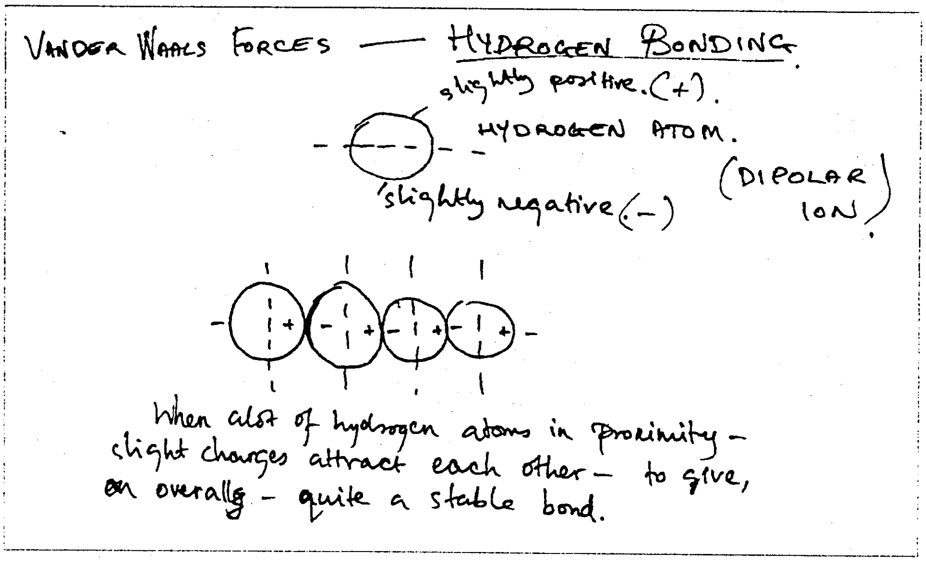
Annie thought that in figure 17 the iodine molecules were held together (A1.728), though *not by chemical bonds* (A1.738), but by "probably *just the forces* of pressure and like the charges from each thing they would be stable" (A1.730). Annie was not clear about what these forces were as she thought that "the forces from each iodine should have combined to stable-up. But, there's probably other forces, which hold it together, in a solid or, so it wouldn't break off or anything" (A1.736).

There were "no" (A1.738) chemical bonds, but there was some other type of force (A1.740). In the second interview she described van der Waals' forces in iodine as,

> "forces holding like atoms together, to form weak bonds, they sort of form weak bonds between each other. And they're, they're readily disrupted... they're more easily disrupted, than would be the bond between the two elements [atoms?] within a molecule."
> A2.407

In her third interview Annie suggested that in iodine "it's ***not bonding***. But there's sort of van der Waals' forces" (A3.140).

In Carol's final interview she was asked what kinds of chemical bonds there were, and she listed "covalent, ionic, dative" (C3.4), then tentatively suggested "what about van der Waals?", before qualifying this with "they're just forces aren't they?" (C3.4). On reflection Carol was now prepared to *consider* that these were "kind of" bonding "because ... they come up in Raoult's law" where "whether something has got positive or negative deviation depends whether it has more or less bonds on mixing." (C3.6). This consideration of deviation from Raoult's law led to her next considering "dipole-dipole attractions", but she did not "know whether they're bonds or not really" (C3.6) She pointed out that these interactions were "not to do with exchanging electrons or sharing electrons" (C3.6), at which point she decided to limit her categories of bonds to "covalent, dative and ionic really" (C3.10).



Jagdish's figure for van der Waals' forces/hydrogen bonding, November 1992

When Jagdish was shown focal figure 17, she recognised "a covalent bond between the two iodine atoms which make up the molecule" (J1.B010), but otherwise did not "think there's a bond, but there is a force" (J1.B017). Jagdish was aware of van der Waals' forces early in her course, and this was one of the three categories of chemical bond that she drew out during a research session in her first term, although her portrayal demonstrated some confusion with hydrogen bonding.

So at one level she considered van der Waals' forces to come under the heading of chemical bonding. However, elsewhere there is some evidence that Jagdish did not consider this type of interaction to be chemical bonding in the same sense as ionic or covalent bonding. In the third interview when Jagdish referred to van der Waals' forces, she suggested "they're *just* induced dipoles" (J3.A099). In a concept map set as a revision task just before the end-of-first-year examination Jagdish wrote that,

> "28. Van der Waal's forces are essentially induced dipole - induced dipole forces. 29. And they are known as transient fluctuating dipoles as the dipoles are not permanent and are constantly changing, this is what makes the V.D.W only weak forces."
> (June 1993).

Elsewhere on the concept map Jagdish describes van der Waals' forces as "the *bonds* between individual molecules", but in the structure of the map only five categories of bonding are directly connected to the focal concept of 'chemical bonding': 'ionic bonding', 'covalent bonding', 'metallic bonding', 'polar bonds' and 'dative bonding'. (The map is reproduced above, §A40.4.1.)

In his second interview Kabul suggested that in iodine there were "weak intermolecular forces", called "Van der Waals' forces" (K2.A253). However he could only explain these as "weak forces which just hold the atoms together" (K2.A260). He also explained that phosphine did not have a giant molecular structure as "the molecules of phosphine are held by weak intermolecular forces, like van der Waals' forces" (K2.A561), "so between two molecules, there is a weak, van der Waals' forces and not covalent bonds" (K2.A572). There were strong covalent bonds within a molecule, "but not between phosphine molecule and another phosphine molecule" (K2.A581). During the fourth interview Kabul discussed focal figure 17. He recognised covalent bonding (K4.B264). He did not think there was any other type of bonding present, but there were "some *forces*", which were "van der Waals' forces" (K4.B268). He explained that,

> "these are the forces which arises due to the presence of dipole. These are neither ionic, or covalent, you know. *Just an attraction and repulsion* between atoms."
> K4.B271

The implication here is that, for Kabul, ionic and covalent bonds are more than just attractions and repulsions between atoms.

At the beginning of this same interview Kabul had defined chemical bonding as "just an interaction between atoms" (K4.A038), yet when Kabul explained how dipoles could arise and lead to an attraction between neutral molecules he did ***not*** class this as bonding,

I: Is there say an attraction between this molecule and this molecule?
K: This molecule and this molecule, yeah.
I: Yeah, ... so exactly how does that attraction work? What attracts what?
K: Like. You know, this is an, it shows an electron cloud,
I: Uh hm.
K: at one time, although they are neutral atoms, at one time, it's possible that, as electrons are, you know, fast moving, it's possible that at one time electrons will be over here, and at the at the same time, you know, let's say electrons electron of these will be over here,
I: Uh hm?
K: ... so electrons from here will - will have a charge of minus, negative, and over here we'll have positive charge, so there'll be an attraction between them.
I: I see. And that's called van der Waals' forces?
K: Yeah.
I: But you wouldn't call that bonding?
K: No.
K4.B277

At the end of the first year of his course Kabul prepared a concept map on 'chemical bonding' as a revision exercise. On his map he divided covalent bonding into two types: "simple covalent bonding" and "giant molecular bonding". One of the "properties" of the former category was "low melting temperature" "because there are weak forces (***no bonds***) between individual molecules" (concept map on 'Chemical Bonding', June 1993.)

In Lovesh's first interview he considered focal figure 17, which he thought contained lots of iodine molecules, with covalent bonding (L1.A491). Although the diagram showed the molecules arranged as in a solid, Lovesh did not think there were any bonds between the molecules (L1.A497). In an interview near the end of the first year of his course Lovesh was asked to list the types of bond he knew of. He classed intermolecular interactions separately as "intermolecular attractions, like van der Waals' forces and hydrogen bonding" (L3.A105). Similarly in focal figure 17 Lovesh did not describe the intermolecular forces as bonds, but again labelled them as attractions, so he recognised "covalent ***bonding*** between the iodine atoms, and there's an ***attraction*** between the iodine molecules as well" (L3.A464). At the same stage in Umar's course he also described the molecules with covalent bonds in focal figure 17 (U3.B270), but when he was asked if there was any ***bonding*** between the molecules, he suggested instead that there "might be some ***attractions***" (U3.A283).

In focal figure 26 Mike thought "there appears to be attraction between the electrons [of one iodine molecule] and other molecules" (M1.B427). Mike recognised the presence of "some attraction", but he would not call this bonding as "they're not joined together" (M1.B427).

In Tajinder's first interview he described interactions between the iodine molecules in focal figure 17 as "not actually bonding, [rather] it might be the positive-negative attraction" (T1.B493). He went on to suggest "there's a force, but *it's not a bond*" (T1.C004). Tajinder thought focal figure 26 represented a different molecular solid, oxygen, but interpreted the interactions between molecules in a similar manner, as "some force ... holding it together", but not chemical bonds (T1.C162). In his eighth interview, near the end of his first year, Tajinder was asked to list types of bond, and at this time included van der Waals' forces. However, he did not seem sure whether to categorise this as a form of chemical bonding or not,

> "This is also a type of bonding, but it's not, it's actually a type of force, *it's not actually a chemical bonding*. What are we doing, chemical bondings, ain't we? ...Yeah, this I think could be counted as chemical bonding, but ... one molecule is not actually chemically linked to another molecule, it's *just a type of force*, that's held in, holding them together."
> T8.A289

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