This is the author's manuscript version.

The version of record is: Taber, K. S. (2000). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education*, 22(4), 399-417. https://doi.org/10.1080/095006900289813

Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure

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Abstract

Some literature reports how learners' alternative ideas in science may be coherent, stable and theory-like. However, other commentators suggest that the available data supports the view that children's thinking is inconsistent, with elicited notions being piecemeal, ad hoc and deeply situated in specific contexts. This is considered to reflect the fragmentary and unscientific nature of the learner's knowledge. Accumulating evidence from in-depth work with individual learners is beginning to show that models of cognitive structure that can usefully inform teaching may need to be more complex than either of these views admit. Evidence from a case study is presented to show how a learner may simultaneously hold several alternative explanatory schemes, each of which is persistent over time and applied coherently across a wide range of overlapping contexts. It is argued that the manifold nature of learners' conceptions may be a key to modelling conceptual development.

Introduction: a claim about cognitive structure

Learning may be considered as a change in the stable elements of cognitive structure (Petri & Niedderer 1998), which I will define as *the facts, concepts, propositions, theories, and raw perceptual data that the learner has available any point in time, and the manner in which it is arranged* (Taber 1997a, after Ausubel & Robinson 1969, and White 1985). Research into how learning occurs in science is therefore informed by the researchers' conceptualisations - explicit or tacit - about the nature of cognitive structure. This paper makes a claim about the nature of cognitive structure: a claim that derives from empirical data, and which has consequences for the way in which learning may occur.

Evidence will be presented to show that an individual learner can simultaneously hold in cognitive structure several alternative *stable* and *coherent* explanatory schemes that are applied to the *same* concept area.

This is a significant claim as research evidence that learners apply several different conceptions to a concept area has been interpreted as implying that their thinking is not theory-like, but incoherent, fragmentary and closely context-bound (BouJaoude 1991). Whilst this may well *sometimes* be the case, it is demonstrated here that a learner *may* hold manifold conceptions which are each stable and internally coherent, and which are applied across a range of phenomena.

Evidence about the nature of cognitive structure derives from the vast canon of work into learners' ideas in science (sometimes labelled alternative conceptions or frameworks). Despite the great extent of this research (Driver et al. 1994, Pfundt & Duit 1994), it has not led to anything approaching consensus about the nature of cognitive structure: something reflected in the diverse terminology used in the field (e.g. Abimbola 1988; Taber 1997a).

The multifarious nature of cognitive structure

Some authors have interpreted research data as implying that learners' ideas tend to be incoherent and inconsistent, fragmentary and transient (e.g. Claxton 1993; BouJaoude 1991; Kuiper 1994; Hennessy 1993; Linder 1993; Russell 1993; Solomon 1984, 1992, 1993; Viennot 1979, 1985) - and perhaps sometimes simply created in response to the social pressure of the researcher's questions (Solomon 1993; c.f. Edwards and Mercer 1987). As Johnson and Gott point out, "a supposition that children 'will have ideas' is not a sufficient basis for according such status to any response" (1996, p. 563). Claxton has suggested that it is naïve to infer that learners have alternative frameworks based on the utterances collected during research. He interprets such utterances as indicating 'minitheories' that are "fragmentary and local" and often "developed in response to particular experiences, predicaments or needs" (1993, pp.46-47.) BouJaoude concludes from research into ideas about burning that students' ideas were "fragmented, inconsistent, and task-specific". BouJaoude strongly emphasised these conclusions, and reported finding "no evidence" for a "coherent set of ideas" (1991, p.693),

> The understandings of these students were fragmented, inconsistent, and based on the visible aspects of the events that they observed. T he students did not seem to have unified their understandings about burning into a coherent set of ideas to explain all their observations of burning things.
>
> (BouJaoude 1991: 700)

However, Watson and coworkers found more consistency in their own study of students' ideas about combustion, and these authors suggest a different interpretation of the data (Prieto, et al. 1992; Watson, et al. 1997).

Indeed, many researchers have interpreted research data as evidence that learners may construct alternative explanatory schemes that *are* theory-like: that is, consistent, coherent, applied over extended periods of time and being applicable across a range of phenomena (e.g. Andersson 1986; de Posoda 1997; Driver & Easley 1978; Driver et al. 1985; Tytler 1998a; Vosniadou 1992; Watts 1982, 1983a, 1983b). It is these researchers who tend to refer to intuitive theories, naïve physics and alternative conceptual frameworks.

The tenacious nature of learners' 'alternative frameworks' was emphasised by those researchers who first brought 'children's science' to wide notice (Driver 1983; Gilbert et al. 1982; Watts 1983a; Watts & Gilbert 1983), as was the way such alternative frameworks could be coherent and sensible from the child's perspective (Gilbert et al. 1982; Gilbert and Watts 1983; Pope and Gilbert 1983; Watts 1983b). More recent studies have led to similar conclusions,

> The success of our research in identifying these models [of the earth in space], and in determining that they are used in a consistent and synthetic fashion, shows that conceptual knowledge is not as fragmented and unconnected as some theorists have argued . . . It appears that students try to synthesise the information they receive from adults and from their everyday experience in a coherent fashion.
>
> (Vosniadou 1992; 350)

It is suggested here that neither view is likely to be exclusively right: research has now been undertaken over a wide range of science topics, with learners at different ages and with varying abilities. It would seem plausible that some data represents learners applying their stable coherent conceptual frameworks, whilst other data reflects the paucity or fragmentary nature of some individuals' knowledge about certain topics. Indeed it would seem likely that cognitive structure includes representations at varying grain sizes, and with different degrees of coherence and integration, held with various levels of commitment (c.f. Niedderer & Shecker 1992; Smith et al. 1993).

Given the likelihood of researchers being able to elicit evidence for learners' knowledge that is both scientifically 'correct' and 'alternative'; both well integrated and fragmentary; both stable and transient; and both self-consistent and incoherent; there is an imperative for research to be based on robust methodology.

The interpretation of 'multiple frameworks'

In 1982 and 1983(a, b) Watts published research findings about learners' conceptions of energy, force and gravity. He characterised common features of his interview data as sets of alternative frameworks. Yet he acknowledged that "some pupils use more than one framework" (1982, p.117). *If* one expects learners to think coherently and *to be consistent* then this throws doubt upon the how well the researcher's models (the alternative frameworks) reflect the learners' ideas. This was recognised at the time as an issue for the research programme,

> it is far from clear how representative of an individual's thinking a particular framework is. Indeed given the manner in which such frameworks are obtained from interview (and other) data, it may well be that an individual's conceptions make use of several frameworks.
>
> (Gilbert and Watts 1983: 86)

Pope and Denicolo referred to the risk of 'framework spotting' (1986, p.157), and suggested that it would often be *possible* to artificially 'disaggregate' a learner's statements into smaller parts which could independently be fitted to the different frameworks that a researcher had proposed. However, they felt that such a process would *not* always lead to an authentic representation of the learner's 'intuitive theory'. The learner's statements often seemed to genuinely encompass several categories that the analyst considered distinct. The data suggested that learners often seemed to apply *multiple frameworks* (p.158).

More recent work has continued to produce similar findings - individual learners apparently utilising several alternative conceptual frameworks, with particular frameworks being sometimes elicited, but sometimes not (e.g., Caravita & Halldén 1994; Maloney & Siegler 1993; Petri & Niedderer 1998; Taber 1995a, 1997a; Taber & Watts 1997; Tytler 1998a; Watson et al. 1997).

This leads to a key question about the adequacy of the research process: i*f a researcher presents a set of alternative conceptual frameworks for a topic as a representation of the range of conceptions found in a sample of learners, but the data from the individual learners reflects multiple frameworks*, then is this because of:

- an *inadequacy in the researchers' models, which do not match the data well;*

or because

- *some learners hold several explanatory schemes for the concept in cognitive structure, and so the multiple frameworks are an authentic reflection of these manifold conceptions?*

This paper argues that - at least in some cases - multiple frameworks are genuine evidence for the manifold nature of learners' conceptualisations. However, a convincing case for this position rests on a particular methodological approach.

Any claim that *an individual learner can simultaneously hold in cognitive structure several alternative stable and coherent explanatory schemes that are applied to the same concept area* rests upon the collection and careful analysis of an extensive data set. The data collection needs to include a wide range of opportunities to elicit the learner's thoughts in different contexts, and over an extended period of time. As Pope and Denicolo suggested "the very choice of intuitive theories as a focus of investigation represents an epistemological stance consistent with the qualitative-interpretative approach" (1986, p.154). Yet much 'alternative conceptions' research has been limited by the investigators suffering restricted access to learners, and consequently having relatively impoverished data (Watts 1988, Black 1989). Often researchers have 'one shot' at data collection from any specific individual learners (Gilbert and Watts 1983, p.87).

Whilst attempts to catalogue the range of alternative conceptions in a population may best be served through approaches which collect data from large numbers of informants, research that is concerned with the structure and dynamics of learners' thinking rests upon case studies. By looking at individual learners in depth, over extended periods of time, the conceptual development research programme is moving beyond the 'butterfly collecting' stage of listing alternative conceptions (Gilbert and Watts 1983; Watts 1988; and Black 1989).

Such studies require careful analytical approaches - such as Johnson and Gott's 'neutral ground' (1996), Petri & Niedderer's 'iterative hermeneutic interpretation procedure' (1998), or, as in the present study, grounded theory (Taber 1997a, in preparation - a). Being longitudinal, such studies are slow to produce results. Nevertheless, a canon of such work is being established in the literature. Examples include Ault, Novak and Gowin's study of the development of the molecule concept (1984), and more recent studies concerning conceptual development in topics such as basic particle theory (Scott 1992; Johnson 1998), atomic structure (Petri & Niedderer 1998), chemical bonding (Taber 1995a, 1997a), electricity (Schwedes & Schmidt 1992), force and motion (Hewson & Hennessey 1992) and air pressure (Tytler 1998b).

Domains of knowledge

The claim argued in this paper, that learners may have manifold stable coherent conceptions for some science concepts, is not the same as the claim that learners may compartmentalise formal science learning away from their informal notions. This *two outcomes perspective* is where pupils learn presented theories and explanations, and can use them in class, but revert to their existing ideas in everyday conversation and problem-solving (Gilbert et al. 1982). This view is supported by many studies that suggest that learners are more likely to apply scientific principles if questions were set as formal exercises with obviously 'scientific contexts', but they often tend to revert to using their alternative frameworks in novel - and particularly 'everyday' contexts (Bliss et al. 1988; Driver 1983; Dumbrill and Birley 1987; Viennot 1979, 1985; Palmer 1997).

Solomon has developed these ideas to suggest that one should distinguish between two systems of knowledge: *life-world knowledge* and symbolic universes of knowledge (such as the theories of formal science). She 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" (1993, p.96). 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*. Claxton has even suggested that learners "should keep the two domains distinct" (1986, p.126).

However, the manifold conceptions discussed in this paper are *not* considered to belong to such different domains. For example, Petri and Niedderer discuss the case of a learner's developing conceptualisation of atomic structure. At the end of their study they consider that "Carl's cognitive system is an association of co-existing conceptions" (1998, p.1083). These were conceptions such as a planetary atomic model, and an electron cloud model: ideas from within what Solomon would call a symbolic universe of knowledge, not the life-world. In a similar way, the manifold conceptions of the learner discussed in this paper all derive from the symbolic world of science, not the informal world of everyday experience. Knowledge *is* somewhat compartmentalised within cognitive structure. So learners may fail to see the relevance of their physics lessons during their chemistry classes (Taber 1998b), and a claim for manifold conceptions in cognitive structure *is* a claim for *a degree of knowledge fragmentation*: but *within* the domain of abstract scientific knowledge.

Evidence from a case study

Methodology

The data reported below were collected during an interview-based study of the development of the concept of chemical bonding with students studying pre-University ('A level') chemistry in a college in England (Taber 1997a). A grounded theory approach was employed (Taber in preparation-a). Students were interviewed for periods that often exceeded an hour, and at several points during their course, so that the stability of their ideas could be explored. The in-depth interviews, usually using simple line-drawings of atomic and molecular structures as foci, were triangulated by the collection of supplementary data - including samples of written course work and the use of Kelly's repertory test. This detailed, longitudinal, approach made it possible to distinguish comments that reflected underlying stable aspects of cognitive structure from those which appeared to be more ephemeral in nature. One of the colearners in the research, referred to as Tajinder, undertook 23 tape recorded interviews during his two year College course (denoted as T1 - T23), providing a substantial data base for analysis. (Details of the analytical process employed in the research may be found in Taber 1997a.)

As is inevitable in any detailed idiographic study, the process of data reduction to produce a narrative report loses much of the complexity and sophistication of Tajinder's thinking (Pope and Denicolo 1986). In this paper evidence has been selected to make a particular argument, but care has been taken to ensure that the account given is authentic. Quotations have been ‘tidied’ (by editing some repetitions and hesitations) to aid readability, but not to change apparent meaning.

Tajinder’s manifold conceptions for bonding

During his course Tajinder commonly explained the chemical bond in terms of three distinct explanatory principles, each of which was applied in a wide range of contexts (Taber 1997a; Taber and Watts 1997). If Tajinder was asked why a bond was formed he was likely to respond in three different ways, which may be paraphrased:

- so that atoms could obtain full shells;
- to give a lower energy level;
- because of the attractions between charged particles.

Although at the *start* of his course only the first of these conceptions would be elicited, the adoption of the other two explanatory principles did not result in the disuse of his earlier type of explanation. Tajinder’s progression in understanding the bonding concept in chemistry may be understood in terms of *the shift in the extent to which each of these three principles were employed* (Taber 1997a; in preparation - b). The concern of *this* paper is to establish that Tajinder’s explanations reflected the coexistence of stable manifold explanatory schemes in cognitive structure.

In order to make my case for the manifold nature of cognitive structure I will provide evidence to show that Tajinder’s explanatory principles for making sense of chemical bonding were indeed stable alternative conceptions. To do this I shall show that Tajinder applied

- each of the principles over *an extended period* of many months, so that they each reflect some stable aspect of cognitive structure;
- each of the conceptions in *a range of ‘chemical bonding’ contexts*, so that they are indeed acting as explanatory principles rather than isolated facts about particular examples;
- *more than one* of the principles to *the same specific examples* (sometimes in the same interview), so these are indeed *alternative* explanatory principles that were employed.

The octet rule explanatory principle

When Tajinder commenced his College course he explained bonding in terms of an explanatory principle based on the 'octet rule', with atoms *actively* seeking to obtain full shells of electrons (Taber & Watts 1996). It is possible to characterise Tajinder's arguments as follows:

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.

This rationale for explaining bonding was in evidence from the first interview, soon after Tajinder commenced the course. For example he explained the covalent bond in a hydrogen molecule in the following terms:

> It's where electrons are shared, by each of the shells, because the first shell needs two electrons to become stable, and this [hydrogen atom] only contains one so it goes to another hydrogen, or it joins with another hydrogen, and it shares the other hydrogen's electron, so it thinks that it's got two electrons, then it becomes stable. (T1)

Tajinder continued to use this type of explanation of covalent bonding during his course. In his third term he explained that a covalent bond was "where two atoms share electrons *to gain a full outer shell*", as if two atoms "join together, and they have a *full outer shell*, then they'd be more stable" (T3). At the end of the first year of his course Tajinder explained that atoms,

> join up with other elements [sic, atoms] who also want to like share electrons. . . . because chlorine has seven outer electrons it needs one electron to have a noble gas configur[ation], or think it has a noble gas configuration. (T9)

This type of explanation was still elicited in Tajinder's second year, so for example, he explained the bonding in carbon dioxide in the following terms,

> It's because the carbon wants to gain a full outer shell, consisting of eight electrons, and it already has four, so all it has to do is gain another four, so it can share, 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 its sort of stable. . . . And also, the oxygen wants two electrons to become stable, so it sort of shares two with carbon. (T10)

Later in the same term Tajinder referred to how an atom in an oxygen molecule would share electrons "so it thinks it's got eight" (T14). In the second term of his second year Tajinder described how "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" (T17). When discussing a free radical reaction mechanism Tajinder explained that the carbon atom in the methyl radical "wants a full octet" (T18).

In the final term of his course Tajinder explained how the polar bond in the water molecule holds the atoms together because the "atoms make up a full octet, or they think they do", so when bonded the oxygen atom "thinks it's got a full octet which is … noble gas configuration" (T19). Just a few weeks before the end of his course Tajinder described how a bond would form between molecules of aluminium chloride and ammonia, to give an adduct, as the aluminium atom "wants a full octet" (T22). Similarly aluminium chloride would dimerise "in order to form a full octet for each of the species involved" (T22). These examples show Tajinder applying the same basic explanatory principle to discussion of covalent bonds (in a range of chemical substances) over a period of seventeen months.

Tajinder also used his octet rule explanatory principle to discuss ionic bonding over a similar time scale. At the start of his course Tajinder explained the ionic bond in sodium chloride,

> If we take sodium and chlorine, an ionic bond is where the sodium loses one electron on its outer shell to the chlorine which contains seven on its outer shell, and this one transfers to this one, so they are bonded. T hey' re ionically bonded. So [an] 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)

In his second term he saw ionic bonding in terms of "an atom which would want to loose an electron, and one which would want to gain an electron" (T2). By his third term Tajinder's explanations in terms of *full shells* ("sodium, to gain a full outer shell, wants to lose an electron, and chlorine wants to gain an electron to become a full outer shell" (T3)) were supplemented by references to *noble gas configurations* ("where an atom either loses or gains an electron to enable it to have a noble gas configuration" (T8)), but he used both terms as synonymous with *octets*,

> Ionic bonding is, in simplistic terms, when you have two atoms, they 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 sodium gives it to chlorine, that's ionic bonding in simplistic terms. (T8)

Although Tajinder tended to use sodium chloride as his archetype ionic material, he applied similar arguments in the case of lithium iodide, where "lithium … wants two electrons in its outer shell to become stable, so … therefore it wants to lose an electron, and iodine … [has] got seven electrons in the outer shell … and the lithium atoms donate electrons to iodine atoms" (T9).

During his second year Tajinder continued to discuss the ionic bond in 'octet rule' terms. He thought the bond between hydrogen and chlorine should be ionic, as "they want to gain a noble gas configuration, or … stable outer shells, and … they'll both combine forming an ionic bond, where the hydrogen electron is taken by the chlorine" (T11). On other occasions during the year he referred to how one would expect a group 1 element to form ionic bonds because it "wants to lose an electron to become stable, or have a noble gas configuration" (T12), and how "to become stable it wants an octet, i.e. a full outer shell with 8 electrons, similar to noble gases." (T17)

Although Tajinder's octet rule explanatory principle was primarily employed in the contexts of covalent and ionic bonds, he did also try to fit metallic bonding into this scheme. So he explained how, in iron, the,

> Metallic bond is where you have a metal and you have positively charged ions, and you have delocalised electrons which is like a sea of electrons around the ions. . . . so the electron is allowed to move around in certain orbitals, around each of the Fe ions, so it becomes stable, because . . . when it comes down to it the Fe' s formed an octet, so it's more stable. (T17)

Tajinder's octet rule explanatory principle was also used to explain why a neon atom would not form bonds, that is "because it's already got a full outer shell" (T3). In his second year he explained that,

> the most stable atoms in the periodic table are the noble gases, because they have a full outer shell or full octet, so because having a full octet they don't want to precipitate [sic, participate] in bonding, . . . they're happy as they are. (T17)

So during the interviews Tajinder applied his octet rule explanatory principle over a period of many months, in a range of contexts to explain three different types of bonding, and the relative inertness of noble gases.

The minimum energy explanatory principle

It is possible to characterise Tajinder's second explanatory principle for explaining chemical bonds as follows:

- configurations of physical systems can be ascribed an energy level
- ;lower energy is more stable than higher energy;
- physical systems will evolve towards lower energy configurations.

Tajinder did not use this type of explanation when he was *first* interviewed at the start of his course. However, by his third term he *was* beginning to use this principle, suggesting that a criteria for whether bonds would form was "whether, if you had two atoms, and if they joined together, would the energy be lower, would they be more stable" (T3). In the same interview Tajinder employed his minimum energy explanatory principle *alongside* his octet rule explanatory principle in his attempt to explain the bonding in metallic lithium,

> because in [a] lithium atom, there' s one outer electron, so it' s not stable, it can gain a noble gas configuration if it loses an electron, and 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)

At this stage Tajinder does not suggest any physical mechanism by which such a process might occur. In his second year Tajinder described his minimum energy explanatory principle in the context of discussing the bonds in tetrachloromethane,

> everything forms bonds in order to become more stable, or at a lower energy . . . it forms because when each individual atom is by itself it's at a certain energy level, and . . . in order to become more stable it forms a bond with something, in order to decrease the energy that it's at, so it becomes more stable, and that's why species form bond'. (T17)

In the same interview he explained that hydrogen and chlorine should react as "when we have hydrogen gas and we have chlorine gas they're at a certain energy level, but then when they react and they form a new product the hydrogen chloride is at a lower energy than the hydrogens and the chlorines." (T17). In the following interview Tajinder reiterated the general principle,

> reactants start off at a higher energy, and in order 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)

In his final term Tajinder applied this principle to explain why two hydrogen atoms would bond together,

> whenever things bond, or form a bond, it's normally to do with becoming more stable or having formation of lower energy, so that's why things bond, and this is to do with the energy levels so, if two hydrogen atoms come together, they can form a bond, if there's two atomic orbitals they form two molecular orbitals, one which is at a lower energy…so that's why H_2 forms.(T21)

The Coulombic forces explanatory principle

The third explanatory principle that Tajinder applied to chemical bonding was based on orthodox electrostatics. Tajinder demonstrated an awareness of Coulombic principles from his first interview. So, for example, he explained atomic structure in terms of a "positive negative bond" by which he meant that "there's an attraction between opposites, because this nucleus is positive, and these electrons are negative, they attract one another". Tajinder thought that "there's always a attraction between positive and negative" (T1). In an interview in his second term he reported that where the distance between charges was smaller there would be a stronger force, and he also showed an awareness of the possibility of an equilibrium due to balanced forces: "they would balance out until the force of repulsion equalled the force of attraction, and it would just like stay there" (T2).

It is possible to characterise Tajinder's Coulombic forces explanatory principle as follows:

- there is always a force between two charged particles;
- similar charges repel, opposite charges attract;
- the magnitude of the force diminishes with increasing charge separation;
- forces acting on particles may be balanced at equilibrium.

Although Tajinder was aware of the electrostatic interactions between nuclei and electrons from the start of his course, he did not initially identify this with the bonding, which he believed was explained in terms of his octet rule explanatory principle. By early in his second term of A level chemistry, however, Tajinder was beginning to tentatively explain metallic bonding in terms of Coulombic forces,

> there's all the atoms they come together and they join together and there's force between them that holds them together, and they just like stay in a block or a lump, as it were, with all the nuclei together with the electrons floating around, and there's a certain force that holds them together. (T2)

By the third term Tajinder's Coulombic explanation of metallic bonding was less tentative, and he made the definitive statement that "the attraction of the electron to the nuclei, that's what makes the bond" (T3). Near the end of the first year of his course Tajinder reiterated his explanation of metallic bonding as due to electrostatic forces,

> metallic bonding takes place in metals, and this is where, say you have sodium, now sodium doesn't exist by itself in 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. (T8)

By the end of his first year Tajinder had learnt about hydrogen bonding, and he also explained this in Coulombic terms,

> there's a certain type of attraction between the two, and therefore there's a type of bond there, which is not as strong as metallic or covalent, ionic bonding, but there's a type of bond there (T8)

In his final term Tajinder reiterated that the hydrogen bond (in ice) was an electrostatic interaction: "a hydrogen bond is an attraction between a ∂- oxygen and a ∂+ hydrogen in this case." (T19). A week later Tajinder explained how "the two lone pairs of electrons on the oxygen can attract protons from other molecules which can form bonds" (T20). During his course Tajinder came to think more about the role of Coulombic forces in ionic structures. So near the end of his first year he explained "there's a force between positive and negative which attracts them" (T8). Later in the same interview Tajinder tentatively suggested that this attraction *was* the bond,

> sodium has formed positive ions, and chlorine formed negative ions . . . 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. (T8)

Two weeks later, Tajinder described how "because there's positive and negative charges, and electrostatic forces bringing them together, they form into a type of ionic structure" (T9). During the third term of his second year Tajinder explained that the "attraction between the ions" in sodium chloride would not cause the different ions to totally coalesce "because there's repulsions as well" (T20),

> Because this is 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 surrounding electrons, so that there's equilibrium where it reaches, repulsions equal attractions. (T20)

By the second term of his second year Tajinder was able to discuss reaction mechanisms in terms of Coulombic interactions, identifying where charged species "attract one another and they form a bond" (T18). By his final term Tajinder was using his Coulombic forces explanatory principle to discuss covalent bonding, such as in the hydrogen molecule, where,

> there's attractions and repulsions. There's attraction between the nuclei of one hydro- gen 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 arepulsion between the two hydrogen nuclei, and there's a repulsion between the two electrons. (T20)

Tajinder's use of multiple frameworks

The evidence above illustrates how Tajinder developed three explanatory principles to explain why chemical bonding should occur (because atoms need full outer shells; because bonding lowers the energy state; because forces act between subatomic particles in different species). Each of these principles could act as a starting point for developing arguments about chemical bonds.

In practice Tajinder would sometimes develop arguments that incorporated aspects of more than one of his explanatory principles. In an interview in his final term Tajinder discussed the bond in a hydrogen molecule,

> this is a hydrogen molecule, and it came about by two hydrogen atoms which came together close enough for there to be an attraction between opposite nuclei and electrons and vice versa and there's also repulsion between them, and they were at the same energy level when they came, when they were separated, and as they came together, instead of having two atomic orbitals they formed two molecular orbitals which would be a better stability, `cause it's more at a lower energy, therefore it would be more stable, so it can form an antibonding and bonding molecular orbital, with the bonding orbital being at a lower energy. (T21)

The explanation describes the electrostatic *mechanism* of bond formation, and then switches to a *rationale* of bonding in terms of minimising energy. An even more telling example occurred during the first term of his second year, when Tajinder produced an explanation of the dative bond in the aluminium chloride dimer in a mixture of Coulombic forces and octet rule terms,

> there's a force of 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 exposed, and the chlorine comes and attacks it, tries to attract to it, or the aluminium attracts the chlorine, so there is a type of bond there,...because 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 is has, I think. (T10)

Again Tajinder uses electrostatic ideas to provide a mechanism for the process, but calls upon an alternative conception (his octet rule explanatory principle) to provide the rationale.

On occasions, during interviews in the second term of his second year, Tajinder produced multiple explanations for chemical bonding using each of his explanatory principles. During one interview Tajinder discussed the bonding in molecular oxygen. His initial explanation built upon the longest established of his explanatory principles for chemical bonding,

> If we have just one oxygen atom it's got six electrons in its outermost shell . . . and 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 bond together, for both the atoms to have full outer shells or eight electrons in this outer shell, is to share two electrons. . . . each oxygen atom starts off with six electrons in its outermost shell, and it wants to gain two electrons, by some method, to have a full outer shell, eight electrons in its outer shell to become most stable. And a way of doing this is by gaining or by sharing two electrons with another oxygen atom. 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)

A little later in the discussion Tajinder introduced the alternative minimum energy explanatory principle,

> Well an oxygen starts off . . . the electronic configuration is $1s^2\ 2s^2\ 2p^2_x\ 2p^1_y$ and $2p^1_z$, and then it's got two gaps that need to be filled, that can be filled with electrons . . . And to become more stable, or at a lower energy, it can gain two electrons, to move down in the energy state, therefore becoming more stable, and so because there's a gap there, there's a tendency for covalent bonding to occur, as in the case of O_2, 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 bond- ing, or any species takes place in bondings in order to lower the energy state or become more stable. (T16)

Tajinder then proceeded to discuss the oxygen molecule in terms of his Coulombic forces explanatory principle. For two discrete oxygen atoms,

> overall their core charge, which is their nuclear charge minus shielding electrons, is plus six...on each one...Now in the 2px orbital we're already got two electrons in there and the maximum an orbital can hold is two electrons, but in the 2py, there's only one electron at the moment and the 2pz there's one electron, and the orbitals are a sort of a guide roughly to . . . where we think electrons exist, . . . where they spend most of their time due to attractions [and] repulsions between . . . other charges in the atom, or in the species, so there's a plus six charge, and their's six electrons in the outer shell, but there' s . . . a gap in the 2pz and the 2py orbitals, where there's an electron short, where an electron could be filled, and that plus six charge can attract electrons from another species to pull into there, or just to gain an attraction for it. (T16)

So in this interview Tajinder was able to use each of his three explanatory principles as a framework for developing explanations of why oxygen atoms might bond together. When the interviewer (the author) recapped Tajinder's explanations with him, he not only acknowledged these three distinct themes, but suggested that the form of explanation he would apply would change with question context,

> I don't think any single one is totally correct, I think you can take bits out of each of them to make a best answer . . . Depends whatever situation I'm in. (T16)

In the following interview, about four weeks later, Tajinder used elements of the three explanatory schemes to discuss the bonding in molecular hydrogen. He began by applying his octet rule explanatory principle,

> the easiest way of becoming more stable or having a full octet [sic] is by sharing electron with another hydrogen . . . they wanna become more stable, so they wanna full octet (T17)

Then Tajinder turned to call upon his Coulombic forces explanatory principle,

> on the atoms there is the nucleus which is positively charged and there are electrons which are negatively charged, and opposite electrostatic forces [sic, charges] attract, and there's an attraction between one nucleus and adjacent electrons on another atom, so that interaction also forces the atoms together, and that forms a bond . . . the positive nuclei attract adjacent 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)

Later he returned to consider octets, but related this to his minimum energy explanatory principle,

> So when you have two hydrogen atoms separately, they have one electron each and to have a full octet [sic] 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)

So Tajinder again demonstrated his manifold conceptions for chemical bonding.

Discussion

The evidence presented in this paper, although necessarily a small part of that collected in the case study, clearly indicates that Tajinder held three discrete explanatory principles for chemical bonding in cognitive structure. Each of these principles was used over many months, in a range of overlapping contexts. Although Tajinder sometimes shifted between these principles in particular explanations, they were not integrated parts of some wider explanatory scheme. Yet, although his thinking about bonding was somewhat fragmented, nor were these alternative conceptions located in separate domains (cf. Solomon 1992). Indeed, for Tajinder, the three explanatory principles were all part of the abstract world of college chemistry. From the perspective of orthodox chemistry, the octet rule explanatory principle is deeply flawed (Taber 1995b, 1998a) and the minimum energy principle would not be considered to be independent of the Coulombic forces principle; but to Tajinder himself, the three conceptions were viewed as alternative narratives that could be employed to make sense of chemistry.

This one case shows that when data from an individual learner seems to be explained best by multiple frameworks, this may - *in principle* - be an authentic reflection of the manifold nature of that learner's conceptualisation. Each case, however, needs to be considered on its merits, and - as Kvale (1996) points out - the extent to which the findings from a case study may be generalised requires a 'reasoned judgment' (p.233) on behalf of the reader. This research was carried out with a College student, someone of greater maturity than the subjects of many research studies. Tajinder's self-confidence, subject knowledge, powers of verbal expression and metacognitive ability were all well above what might be expected in many studies focussing on school-age learners.

Accepting that some students *may* hold stable manifold conceptions in cognitive structure does not imply that *all* apparently contradictory or incoherent explanations collected from science learners may be explained in terms of 'multiple frameworks'. Sometimes, as Pope and Denicolo (1986) imply, the researchers' analyses may have failed to identify the complexity and subtlety of the learners single coherent intuitive theory: it is well accepted that interpreting learners' ideas is problematic due to the alternative meanings given to the same words (Watts and Gilbert 1983), and the unfamiliar nature of the concepts themselves (Viennot 1985). Similarly, as Claxton points out, some data may be "ephemeral reflections" of the *process* of learners constructing ideas *in situ* (Claxton 1993, p.45). Ault, Novak and Gowin note that although people *may* indeed hold "multiple, contradictory notions": some of those elicited in research may well be "transitory artifacts" of the interview itself (1984, p.447).

The principle that cognitive structure *may* have a manifold nature should not in itself be surprising. Both the historian of science and the researcher into children's science demonstrate that it is possible for an individual to learn several versions of a concept - often sharing some common propositions - even if most are alternative frameworks constructed to represent what is understood about *other* people's ideas about the concept (Taber 1997a). This ability to construct alternative understandings of a topic, without committing to them, could be a key aspect of conceptual change. This notion is especially strong in the writing of Thagard (1992). Thagard studies the historical development of scientific concepts, but has produced a model of conceptual change that is applicable to the individual learner. He argues that for a conceptual revolution to occur (such as the oxygen theory replacing phlogiston, or when a school pupil comes to see force being proportional to acceleration rather than to speed), the new conceptual structure has to be built, and explored, whilst the existing beliefs are in place. When the new framework is found to have advantages over the existing one it will tend to be used more, and the previous ideas will fall into disuse. Thagard defines the criteria for comparing frameworks as 'explanatory coherence', and his ideas may be seen to have much in common with the conditions for rational learning discussed by Strike and Posner (1985, 1992): i.e., 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.

Such a perspective naturally admits the possibility of transitional states of belief in one's frameworks. It is possible to imagine the chemist not yet fully convinced by oxygen theory, but beginning to consider that it may be ultimately more fruitful than the more familiar phlogiston approach. Similarly the school student gradually learning more about the accepted concept of force might be expected to largely rely on her familiar 'intuitive physics' until, after sufficient familiarity and practice, the curriculum science version comes to have greater explanatory coherence. During this transitional phase the student can not be said to fully believe or accept one framework and fully disbelieve or reject the other. Watson et al. suggest that apparent inconsistencies in ideas about burning elicited from some of their sample could be due to these students being "in a state of transition from theory to another" (1997, p.437).

Indeed, there is no reason to assume that it is the usual case that complete conceptual revolution occurs and one framework comes to be exclusively used. Over time Tajinder shifted away from using his octet rule explanatory principle, but it still featured strongly in his thinking at the end of his course. A learner discussed in another case study (Taber 1995a) commenced her college chemistry course with an alternative meaning for the '+' and '-' symbols used to label ionic charges. Explanations elicited during research interviews, *after* she had acquired the accepted scientific meanings, were sometimes constructed around one meaning and sometimes around the other. Maloney and Siegler suggest a similar situation in physics,

> For years after encountering physics concepts, students may posses not a single coherent understanding but rather a variety of alternative understandings that coexist and compete with one another.
>
> (Maloney & Siegler 1993: 283)

Tytler has reported that primary age pupils may demonstrate what he labels 'multiple perspectives' as they attempt to provide explanations they find satisfactory (1998a, p.912). In Petri & Niedderer's discussion of their case study of learning about atomic structure, the authors describe the final state of their informant's cognitive system as having "several conceptions co-exist[ing] … with a metacognitive layer on top" (1998, p.1083). Similarly, in the present study, Tajinder completed his chemistry course holding three discrete explanatory principles for explaining chemical bonding, and he recognised that he could select whichever principle seemed most appropriate for a particular situation.

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 a 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" (1968 {1940} , p.21). Perhaps our cognitive structures *typically* comprise of manifold competing conceptions for many concepts. In a world where the information available on any topic is usually partial, and often apparently contradictory, effective decision-making could often depend upon the plurality of our cognitive structures. Ault, Novak and Gowin found that rich conceptualisation was a good indicator of subsequent conceptual development,

> Understanding evolves slowly from poor conceptualization; rich conceptualization, whether with standard or idiosyncratic meanings, enhances understanding over time . . . despite the persistence of `non-standard' or idiosyncratic meanings.

Indeed it has been suggested that in chemistry, due to the nature of the subject, students might sensibly consider the concepts, theories and models of their subject as a kit of mental instruments from which they can select the appropriate 'tool for the job' (Taber 1995c, 1997a). Within the formal scientific curriculum there are alternative definitions for such concepts as 'oxidation' and 'acid'. If Tajinder was expected to accept that oxidation may be the addition of an oxygen atom, the loss of an electron, or an increase in a number (oxidation state) assigned according to a list of rules: why should bonding not be variously explained as obtaining a full shell, minimising energy or the effects of electrostatic forces?

Carr (1984) has suggested that confusing the different models used in chemistry is a significant problem for learners. Tajinder's octet rule explanatory principle is based on a useful scientific heuristic, but overgeneralised to contexts where it is not valid (Taber 1995b, 1997a, 1998a). Linder has emphasised the importance of the learner *selecting* an *appropriate* conception for a particular problem,

> Because it would appear natural for a person to construct a variety of conceptions of phenomena, what would, then, seem to be important is the ability to recognize a context and, in terms of this recognition, evoke an *appropriate* conception.

An unanswered question is: *what lessons may be drawn from the present study for teaching ?* Perhaps the most significant point is that teachers need to appreciate that assessing learners' knowledge is a complex process. Questions such as:

- has the learner attained concept X?

and even

- does the learner apply principle Y in context Z?

will not do justice to the potentially manifold nature of cognitive structure. As Maloney and Siegler argue, a full assessment of the learner's knowledge base needs not only to specify a student's conceptions, but also "the conditions under which the student thinks each concept applicable" (1993, p.294). Ebenezer & Erickson have referred to how an individual student can "employ varying conceptions, depending upon *their assessment* of the contextual features for a *particular* setting" (1996, p.185, emphasis added).

As we have seen with Tajinder, a learner may try out several alternative conceptions in the same context where they are believed to be potentially useful. The teacher should perhaps be encouraging learners to think of scientific concepts, models, principles and definitions as a mental toolkit (Taber 1995c), and taking a role of developing students' proficiency in selecting and applying appropriate tools in varying contexts. The research reported in this paper supports Smith and coworkers' viewpoint of seeing "students' prior conceptions as a resource for cognitive growth within a *complex systems* view of knowledge" (emphasis added),

> This theoretical perspective aims to characterize the interrelationships among diverse knowledge elements rather than identify particular flawed conceptions; it emphasizes knowledge refinement and reorganization, rather than replacement, as primary metaphors for learning; and it provides a framework for understanding misconceptions as both flawed and productive.

At the start of this paper I set out a claim about the nature of cognitive structure which has consequences for the way in which learning may occur. Where the plurality of concepts held in cognitive structure is accepted *it is possible to use such manifold conceptual schemes to explore conceptual development.* Where alternative conceptions are considered to naturally coexist as part of a mental toolkit, then it is possible to study conceptual development in terms of the changing extent to which the alternatives are selected over time as the learner develops both the conceptual frameworks themselves, and judgments about the contexts in which they are best applied. Such analyses will again require in-depth case studies of individual learners, and it is intended to explore this aspect of Tajinder's case in a subsequent paper (Taber, in preparation - b).

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