Prior learning as an epistemological block?

the octet rule

- an example from science education

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Abstract:

Two decades of research in science education have examined young peoples' ideas prior to formal teaching, and have considered how such preconceptions might act as a block to effective learning of orthodox science. Considerable efforts have been expended in developing activities to challenge 'misconceptions' that are found to be common in such naive thinking, to prepare the way for the desired conceptual changes.

If the learner's lay ideas can act as a block to effective curricular learning, then how much more efficacious could ideas acquired in formal instruction, presented with the authority of the teacher and of science. Science educators accept that the acquisition of complex scientific concepts is not an all-or-nothing event: often there is the need for learners to revisit concepts over a number of years, increasing the sophistication of the exposition, and the range of contexts in which the idea is applied. The concept as met at age 7 will not be presented as fully as when revisited at age 17.

For educators science is a way of knowing the world in terms of models and theories that are judged according to logical, empirical and utility criteria - successful scientific theories comprise self-consistent frameworks of ideas that are not falsified by experiment and which have explanatory value in discussing a range of phenomena. Research shows that science learners do not have the same epistemologies of science: they see science as factual rather than conjectural, as absolute rather than relative, and they may accept as 'explanation' that which is merely definition or tautology, that which is anthropomorphic and/or teleology, that which is merely correlational, and that which is merely description. Consequently care should be taking when introducing elementary ideas that any simplifications and generalisations that are used are not presented in such a way that they might later act as blocks to progression in the development of the concept area.

This argument is illustrated by consideration of what is often known in chemistry as the 'octet rule'. This (used correctly) is a heuristic for determining which chemical species (atoms, molecules, ions etc.) are likely to be relatively stable. Evidence will be presented to demonstrate that for many students this 'rule of thumb' learnt in introductory science courses, takes on the status of a causal framework that is used to 'explain' chemical changes. Atoms and the like are so novel to youngsters that ideas about this world presented with the authority of science seem to become deeply established (there are few preconceptions to interfere.) The idea that atoms need to obtain 'full outer shells' is not only widely applied by students where it is inconsistent on its own terms, but it can act as a block to learning the more difficult ideas about chemical changes met later in science.

Prelude:

A student is in conversation with her chemistry lecturer a few days before her A level examination . They are looking at a diagram showing the formation of the hydrogen molecule in terms of energy levels:

The interviewer had set up a context for the question about the helium molecule - a context in which the hydrogen molecule was being discussed in terms of the atomic and molecular energy levels. The question about helium could have been answered in those terms. Yet when Delia answered she did not talk about energy levels - like those of the diagram being discussed - but instead referred to 'full shells'. My interpretation of this extract is that Delia switched from using an explanatory framework of ideas based around a principle that systems evolve towards lower energy, to an alternative explanatory framework based on a principle usually known as *the octet rule*. The reason I think this is worthy of comment is that both frameworks are based on principles taught in chemistry classes. The teacher-interviewer presented a diagram which set up the dialogue in terms of the more sophisticated principle used in advanced level chemistry, yet the answer was given in terms of the alternative principle which the student had learnt at a more elementary level of her education.

The point is that Delia's answer was *not wrong*, and her reasoning *was* based on prior learning. However, it was not the *appropriate* chemical concept to use in that context. It is argued in this paper that present knowledge can act as a block to further learning, and that the octet rule is an example of such an epistemological block.

Introduction: meaningful learning and learning blocks?

In science teaching we are not concerned with rote recall of arbitrary material, but with *meaningful learning*. **Ausubel & Robinson** (**1969**) state that there are two starting points for what they term 'the meaningful learning paradigm',

> "the most important factor influencing learning is the quantity, clarity and organization of the learner's present knowledge. This present knowledge, which consists of the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to him at any point in time, is referred to as his cognitive *structure*.
> The second important focus is the nature of the material to be learned."
> (**Ausubel & Robinson, 1969**, pp.50-51, *italics in original*.)

Ausubel & Robinson proceed to 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 & Robinson, 1969**, p.53.)

For our present purposes we will assume that the third condition is satisfied - not because this is always the case, but because the present paper is concerned with learning blocks that afflict keen, well-motivated and interested students.

A learner may acquire extensive new knowledge:

> “by *nonarbitrarily* relating potentially meaningful material to relevant established items in his cognitive structure, the learner is 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. It is the very nonarbitrariness of this process that enables him to use his previously acquired knowledge as a veritable touchstone, for internalizing and making understandable vast quantities of new meanings, concepts, and propositions, with relatively little effort and few repetitions. … the only way it is possible to make use of previously learned ideas in the processing (internalization) of new ideas is to relate the latter *nonarbitrarily* to the former.” (**Ausubel & Robinson, 1969**, p.57, *italics in original*.)

The influence of ideas such as these have led to an enormous research effort to find out exactly what learners do already know before formal science teaching (e.g. **Carmichael *et al.*, 1990-2**; **Duit, 1991; Driver *et al.*, 1994**.) There are a number of theoretical approaches in this field reflected in the various terms used to described children’s ideas in science (**Black and Lucas, 1993**.) A term such as ‘intuitive theories’ (e.g. **Pope & Denicolo, 1986**) seems to emphasise the learner’s naÔve interpretations of natural phenomena, whereas ‘lay understanding’ (e.g. **Furnham, 1992**) seems to put the emphasis on acquiring ideas from social interaction. The term ‘misconception’ is often used by teachers, but is seen to imply a mis-interpretation of information formally presented during teaching. A term such as ‘alternative conception’ is often preferred as being neutral in the sense of not actually implying the origin of the notion concerned (**Taber & Watts, in prep.**)

In the present paper the origin of such conceptions is of particular importance because I wish to consider the idea of prior learning acting as a learning block.

I am using the term ‘learning block’ to mean some aspect of existing cognitive structure which interferes with the effective learning of material during science teaching. I am going to suggest that - for present purposes at least - such learning blocks may be divided into categories according to their pedagogic implications.

However, before I consider the ‘blocks’ themselves it is expedient to turn briefly to the notion of cognitive structure. We have already found that Ausubel and Robinson define this as “the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to him at any point in time”, although it might be suggested that this is actually a description of the *contents* of cognitive structure. **White** has considered the definition “the knowledge someone possesses and the manner in which it is arranged” as “ill-defined” (**1985**, p.51), but its 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 present purposes then I will make the following assumptions, that I hope 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 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.
Although this is rather a vague set of precepts, I would suggest it is the axiomatic basis of much science education research!

A possible typology of learning blocks

The first distinction I wish to draw is between what I will call null learning blocks, and substantive learning blocks.

Null learning blocks:

A null block describes the situation where meaningful learning 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. The teacher may act in this situation to make connections explicit.

Alternatively, 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. In this situation remedial teaching is required. A slightly different problem is found where the material to be learnt is highly abstract, and 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 (**Taber, in prep**.)

Substantive learning blocks:

As opposed to null blocks, substantive blocks are not caused by the absence of material perceived as relevant in existing cognitive structure, but rather 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. There are several possible outcomes here:
i) perhaps no learning takes place (i.e. there is no consequent change in cognitive structure) ;
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 re-interpreted 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 . 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 (e.g. **Champagne *et al.*, 1985**.)

It is suggested here that to a first approximation substantive learning blocks 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.

Ontological learning blocks?

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

The term intuitive may seem to suggest that we are in some sense concerned with *a priori* knowledge, perhaps 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 modern explanation might suggest that brain evolution has been constrained by physical law, and yet has been contingent on our environment. For example there has been research into the so-called natural categories that are believed to be recognised across cultures (e.g. **Gelman & 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 brains have evolved. (For such purposes the subtleties of scientific taxonomy may have less utility value, so that in general spiders may be categorised as 'insects', which in turn are not classed as 'animals'.)

Whatever predispositions there may be, actual concept development requires experience of the world. Our beliefs about *the way the world is* are surely 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' .

On the other hand, it may be useful to draw a distinction between learning blocks which may be seen to be largely caused by the deliberate prior teaching of specific material, and those acquired through more nebulous experience. Research tells us that once established alternative conceptions and frameworks may often be very stable, and may act as significant blocks to subsequent intended learning (*e.g*. **Taber, 1995d**.) It is argued here that such alternative ideas may be equally effective as learning blocks, whether they are a learner's 'intuitive theory' about motion based on an impetus framework (**Gilbert & Zylbersztajn, 1985**), or a 'misconception' of taught ideas such as the 'molecular' framework for ionic bonding (**Taber, 1993d, 1994a**). Yet the latter category of learning block may be avoidable in the future by appropriate changes to curriculum, text books and teaching schemes (**Taber, 1993d**, pp.9-10., **1994a**, pp.101-102.) 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

> "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.

It would therefore seem that if such blocks are identified, effort should be made to rethink our teaching approaches to see if we can avoid them in the future. Such substantial learning blocks I will refer to as *epistemological* learning blocks .

type of learning block	***nature of block***	***action required***
deficiency block	no relevant material held in existing cognitive structure	remedial teaching of prerequisite learning (if available), or restructuring of material with bridging analogies *etc.*
fragmentation block	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 block	presented material inconsistent with intuitive ideas about the world held in cognitive structure	make learner's ideas explicit, and challenge them where appropriate
epistemological block	presented material inconsistent with ideas in cognitive structure deriving from prior teaching	for individual learner: treat as ontological block; for future: re-think teaching of topic - order of presentation of ideas, manner of presentation, *etc.*

Table 1. Types of learning blocks.

Epistemological learning blocks?

So an epistemological learning block 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 blocks - alternative conceptions and frameworks developed prior to formal tuition - particularly in physics topics. Much of this research has been from a constructivist perspective, (as this viewpoint leads researchers to expect and respect alternative thinking - i.e. to expect learners to actively construct meaning from their experiences, and therefore to respect the status these ideas have for the learner and the consequences they have for teaching.) There has been less research of this nature in chemistry, beyond elementary topics. Despite the central importance of chemical bonding, there has been little enquiry into students' ideas in this topic area, and virtually none from an explicit constructivist position. I have suggested (**Taber, 1993a, 1995b, Taber &Watts, 1995**),

- learners are unlikely to have 'intuitive' ideas about atoms and chemical bonds, which are not directly experienced;
- conceptual development in this area is difficult to analyse due to the range of models and abstract concepts used;

- understanding chemical bonding relies on a knowledge of force, electrical charge and quantum physics - so research needs to take learner's ideas in these areas into account as well.

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 blocks.

In the present paper there will no attempt to suggest how common epistemological learning blocks are, but rather to illustrate the notion with an example which has taken on particular importance in my research into the development of student understanding of chemical bonding. This example is the octet rule, which in various forms is a commonly used idea in introductory chemistry. I suspect that other examples will be found, and one potential candidate may be "the way electric current is defined in the early high school grades, often as 'the flow of electrons' " which according to Garnett and co-workers "may contribute to the formation of … alternative conceptions about electric circuits [in electrochemistry] …[as] Students proceed to apply this limited definition to electrolytes in cells." (**Garnett *et al.*, 1995**, p.85.) In a similar way, in my research I have suggested that knowledge of the octet rule may interfere with subsequent study of other more sophisticated chemical ideas (**Taber, 1994a, Taber 1995c, Taber & Watts, 1995**). I will summarise my argument:

1) the octet rule is a useful heuristic for distinguishing atomic structures that are likely to be stable; however:
2) it is sometimes presented as if it is an explanatory principle;
3) learners may therefore come to understand the octet rule as explaining chemical processes;
4) learners may use the octet rule to 'explain' phenomena, even when the explanations are inconsistent in their own terms;
5) learners may use the octet rule to make false predictions;
6) the development of a conceptual framework based on the octet rule as an explanatory principle hinders the development of more appropriate explanatory conceptual frameworks.

The octet rule

Certain atomic electronic structures, especially the noble gas electronic structures, are found to be associated with a particular stability. Many atoms that do not have these structures tend to form stable ions that do: *e.g.* F^-, O^{2-}, Na^+, Mg^{2+}, *etc*., rather than ions that do not (such as Na^{2-} *etc*.) Stable molecules can usually be drawn as overlapping atomic structures such that each atom has a noble gas structure if electrons in the overlapping region are counted to both atoms. Although this pattern can be explained in terms of higher level chemical ideas, it is normally introduced at an elementary level before such concepts are available.

Limitations of the octet rule

The octet rule does not explain:

- compounds of noble gases;
- the relative stability of molecules such as CO, so-called electron deficient species such as BCl_3;
- compounds with 'expanded octets' such as SF_6, PCl_5.

- the stability associated with certain 'non-octet' electronic configurations such as s^2 and d^5.

However perhaps the most important limitation of the octet rule is that it divides chemical species according to a dichotomy: those that 'satisfy' the octet rule, and those that do not. It does not explain the variations in stability within either class. For example the hydrogen molecule, the chlorine molecule, and the hydrogen chloride molecule all satisfy the octet rule - so the rule cannot offer any insight as to why hydrogen and chlorine react to form hydrogen chloride. We will see below that students may not appreciate this point! This is an important limitation as most chemical processes of interest concern the reactions of such 'stable' species.

The octet explanatory principle?

It is not the purpose of this paper to criticise the octet rule *per se*. It is a useful heuristic that helps learners new to chemistry to

- identify which ions are most likely to be formed;
- work out the valency of elements;
- and therefore to work out the formulae of simple compounds.

However it should be borne in mind that the octet rule does <u>not</u> indicate:

- why noble gas electronic structures are stable;
- why species with noble gas electronic structures should often undergo chemical processes.

Yet evidence from my current research suggest that the octet rule may be used as the basis for an explanatory conceptual framework.

For example, consider the case of a student I will call Tajinder . Tajinder was a 'co-learner' in an interview study - in other words he took part in a sequence of research interviews with the author, from which it was hoped that both would benefit (**Taber, 1994b**). Tajinder was interviewed over twenty times during his A level chemistry course. Analysis of the data suggested that during this time Tajinder explained chemical phenomena related to bonding in terms of three 'explanatory principles' which could be summarised:

a) 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.

b) the electrostatic 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.

c) 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.

The first principle was already used by Tajinder at the start of the course, and only had a limited range of convenience. It will be noted that it has an anthropomorphic component. The other two principles were acquired during his course, and were closer to the 'target' knowledge being taught on the course. Although Tajinder learnt to explain chemical ideas in terms of electrostatic forces, and overlap of atomic orbitals, and managed to use these ideas in more inclusive and sophisticated ways during his course, they never totally *replaced* the octet rule as an explanatory principle.

For example in one research interview Tajinder had drawn a diagram representing a molecule of chlorine and a molecule of hydrogen. The interviewer asked about the possibility of a 'reaction' between the species, and then steers the conversation to the energy changes involved.

Interviewer : Is it possible they would react together?
Taj: Yes.
I: Spontaneously, or would you have to put some energy in?
T: I think you have to give off a spark and they'll react.
I: Will we get the energy back if we did that?
T: Yes.
… [The student draws a molecule of the product.]
I: So why does that reaction occur?
T: … it will be 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, 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: But it was okay putting energy in, because?
T: Yeah. Because the amount of energy [that] was given out, would have, how can you say it, counteract, the amount of given in.
I: More than compensated for it?
T: 'More than compensated', that's right.

There is certainly some 'guiding' here, as the interviewer explores how well the student can discuss the example in terms of energy changes. However, Tajinder certainly seems able to consider the process in these terms. Some time later *in the same interview* the student is referred back to his diagram.

I: Why should there be a reaction between this hydrogen molecule and this chlorine molecule? [pause whilst student thinks - approx. 9 sec.]
T: They <u>want to gain a noble gas configuration, or stable outer shells</u>, and as hydrogen has got an electron which it can get rid of, and the chlorine has got a shell where it can accept an electron, they'll both combine forming an ionic bond, where where the hydrogen electron is taken by the chlorine.
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.

The points of interest in this extract are that:

- Tajinder spontaneously uses the octet rule to explain a process that he had earlier explained in terms of energy changes;
- the explanation given is invalid in its own terms - as the reagent species obeyed the rule as much as the product;
- Tajinder incorrectly states that the reagent species do not have stable electronic structures even though he had drawn the diagram showing the reactants as molecules (not atoms) earlier in the interview.
- The hydrogen-chlorine bond is labelled as ionic, rather than polar.

The relevance of the last point is that Tajinder was familiar with, and quite able to discuss polar bonds. However, the concept of a polar bond can only be explained within an electrostatic framework. In a similar way the hydrogen bond may not be considered a bond (or at least not a 'proper' bond) as it cannot be accommodated within the octet framework . The octet rule framework divides bonds in compounds into the dichotomy of ionic or covalent. Garnett and coworkers have reported that research shows "almost a quarter of [students tested] believed that equal sharing of the electron pair occurred in all covalent bonds." They consider this is "an example of students over-generalising." (**Garnett *et al.*, 1995**, p.76.) My own interpretation would be that these students are thinking in terms similar to Tajinder's octet rule framework, in which atoms donate, share or accept electrons to have the right number - and electrons are either counted towards an electronic structure or not. This type of 'sharing' is such that an electron counts twice - once for each atom sharing - so any argument about which atom has the bigger share is meaningless. In this sense the two frameworks are incommensurable.

The dialogue was then focussed on the electronic structures of the species drawn, and Tajinder accepted his argument was invalid. The discussion continued:

I: So why [would they] react then, if they have already got full outer shells?
[pause of approx. 15 sec.]

T: Is it to do with the electron density, both the chlorines have got the same amount of electron density around each chlorine, and what it <u>wants</u> really is to gain more of the electrons to itself, whilst the hydrogen is <u>not really bothered</u>. No, that's not really very good is it! [He laughs at his use of the term 'not really bothered'.] **So the chlorine reacts with the hydrogen so therefore it can pull in more electrons towards itself, and therefore <u>feel</u> stable - <u>feel more stable</u>.**
[short pause, approx. 3 sec.]
I don't know the answer to that question.

Here Tajinder constructs an explanation in terms of electron density. However, rather than building his argument in electrostatic terms he maintains the use of anthropomorphic language. Even after chastising himself for suggesting atoms may be 'not bothered' he reports that the atoms *feel* stable. This is not because Tajinder was incapable of suggesting a physical mechanism for a polarised bond. In a previous interview he had explained the polarity of the lithium-iodine bond as being "because the iodine has got a much greater core charge." However, my interpretation of the present extract is that once Tajinder had started thinking in the anthropomorphic terms of the octet rule framework, this channelled his ideas into a conceptual *cul-de-sac*, such that - at that moment - he indeed did not 'know the answer to that question' .

For Tajinder a chemical reaction could be said to occur for three reasons:

> 1) because the atoms wanted full shells
> 2) because forces acted between charged particles
> 3) because the product was at a lower energy

and these were complementary views.

To the researcher the *status* of these views was very different. (2) actually suggested some mechanism to explain how change occurred, (3) - at least as used by Tajinder - tended to be teleological, if not tautological, whilst (1) was anthropomorphic, resting on the perceptions and desires of atoms. Anthropomorphic language and explanation in science should not be dismissed as it may have an important role to play in a learner coming to understand the world of atoms and molecules (**Taber & Watts, in press**). However, the existence of a familiar anthropomorphic conceptual framework for explaining chemistry can be seen as a barrier to Tajinder learning to develop and apply more advanced (and scientifically acceptable) notions.

Examples of the use of the octet explanatory principle

For examples I will present two arguments made by Tajinder during the second term of the second year of his A level course.

The first example concerns the covalent bond between two oxygen atoms in the oxygen molecule. Tajinder explained this in the following terms:

> two oxygen atoms want an octet state to become stable
> they want to gain two electrons to have a full outer shell
> so they share electrons
> afterwards they think they have a full outer shell

This explanation was given some considerable time after Tajinder had demonstrated that he could explain both the formation of the covalent bond, and the bond itself, in terms of attractions and repulsions between atomic nuclei and electrons in orbitals. Yet on this occasion his explanation relied on the desires and thoughts of oxygen atoms.

This was not an isolated case, and a further example occurred in a subsequent interview when Tajinder explained the ionic bond in sodium chloride in terms of

> a sodium atom wants to become stable,
> it wants an octet,
> a full outer shell with 8 electrons.

Misunderstanding the ionic bond

It has been argued elsewhere (**Taber 1993d, 1994a**) that the ionic bond is often misunderstood by students commencing A level Chemistry. Further it has been suggested that common aspects of this misunderstanding may be represented as an alternative conceptual framework called the ‘molecular’ framework for understanding ionic bonding . This alternative framework may be seen as constructed on the octet rule explanatory principle. In part this framework may be stated (for the archetype sodium chloride):

- the ionic bond is the transfer of electrons on ion formation
- atoms become ions to obtain ‘full outer shells’;
- a sodium atom has one surplus electron and forms one bond with a chlorine atom which has a deficit of one electron;
- the ion pair that has been involved in electron transfer comprises a molecule of sodium chloride;
- as a sodium atom and a chlorine atoms can each only form one bond, and yet each is surrounded (in the NaCl lattice) by six counter ions, the interactions with the other five neighbours must be ‘just forces’.

The evidence on which this ‘alternative framework’ was originally based consisted of statements made in interviews by a small sample of students. However since then a pencil-and-paper instrument has shown that a significant number of learners seem to share some of the conceptions on which this framework is based (**Taber, 1995e**.)

In a sample of over one hundred A level students who had studied chemical bonding at A level,

60% agreed (and 33% disagreed) that:

> “A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.”

58% agreed (and 34% disagreed) that:

> “A chlorine atom can only form one ionic bond, because it can only accept one more electron in its outer shell.”

58% agreed (and 37% disagreed) that:

> “An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.”

Misunderstanding ionisation energy

Ionisation energy is an important topic in A level Chemistry, as the comparisons made - across periods; down groups; successive ionisation energies - relate to two fundamental topic areas: atomic structure and periodic classification. Understanding the patterns of ionisation energies requires an application of electrostatic principles. For the case of the sodium atom for example, students learn that the outermost electron is attracted to the positively charged nucleus, and therefore force is required to remove it. The size of the force is related to the core charge (*i.e.* nuclear charge minus number of shielding electrons) on the atom and the average distance from the nucleus . However the present research suggests that students commencing A level chemistry may well have alternative conceptions of electrostatic ideas which are inconsistent with the principles used to explain ionisation energies at this level (for example **Taber 1995d, Taber & Watts, 1995**.)

A second obstacle to effective learning may be the use of the octet rule as an explanatory principle. Consider for example the ionisation of sodium just discussed. A level chemistry students will consider the amount of energy required to separate the outer sodium electron from the rest of the atom, compared with the amount of energy required to ionise, say, magnesium, or potassium and lithium. The assumption is that the sodium atom is more stable than the separated ion-electron pair, and therefore work has to be done to ionise the atom. 'Obviously' if the ion and electron were then left in close proximity (in an otherwise empty space) they would be attracted back together as they have opposite charges, and the atom would reform. This is plain sense from an orthodox conceptual framework based on electrostatic principles.

However for many students learning about ionisation energies the sodium ion is more stable than the sodium atom, and therefore the whole notion of ionisation energy must seem somewhat surreal. Again this point was first revealed in discussions in interviews, but has since been followed up with larger numbers using a pencil-and-paper instrument . To date 73 A level students who had studied the topic of ionisation energy have responded to this instrument.

79% agreed (and 18% disagreed) that:

> "[a sodium] atom would be more stable if it 'lost' an electron"

whilst only 11% agreed (and 85% disagreed) that:

> "the [sodium] atom would be less stable if it 'lost' an electron"

and 33% actually agreed (c.f. 62% disagreed) that:

> "the [sodium] atom will spontaneously lose an electron to become stable"

Despite being taught about successive ionisation energies 30% agreed (c.f. 66% disagreed) that:

> "only one electron can be removed from the atom, as it then has a stable electronic configuration"

and - despite the opposite charges involved - 60% agreed (and only 27% disagreed) that:

> "if the outermost electron is removed from the atom it will not return because there will be a stable electronic configuration."

Perhaps the most surprising result from this instrument was the response to the item:

> "the atom would become stable if it either lost one electron or gained seven electrons"

The notion of the Na^{7-} ion being stable is quite contrary to basic chemical 'sense'. This item was included on a hunch . 65 of the 73 respondents (89%) agreed with the item, and only 5 (7%) disagreed.

It was thought possible that the wording of the item could have been ambiguous, and respondents *could* have thought they were agreeing to one of the options,

> either
> the atom would become stable if it lost one electron
> or
> the atom would become stable if it gained seven electrons

To explore this finding a question was prepared based on this one item. It presented respondents with three diagrams representing a sodium one-plus ion, a neutral sodium atom and a sodium seven minus ion. For each of the three permutations of pairs of species the respondents had to chose between three statements describing the relative stabilities. This instrument has been piloted with one group of 16 A level students.

Whilst half the group thought that Na^{7-} was less stable than Na^{+}, the other half thought they were equally stable. Most (13/16) thought the Na^{+} ion was more stable than the sodium atom, and a majority (10/16) also thought the sodium atom was less stable than the Na^{7-} ion. Although one should be careful to interpret data from one small group of students, these findings are part of a consistent pattern.

The students were asked to explain their reasoning. The following response was not atypical:

> "A [Na^{+}] is more stable than B [Na] because its outer shell electron has eight electrons and is full where as B [Na] only has one electron in it's outer shell and is therefore less stable.
> B [Na] is less stable than C [Na^{7-}] because again the outer shell of C [Na^{7-}] is full with eight electrons but B [Na] only has 1 electron in its outer shell and is less stable.
> C [Na^{7-}] and A [Na^{+}] are equally stable because both outer shells are full and the valency requirements have been fulfilled. Therefore both are equally stable."

Some of the students seemed to recognise the novelty of Na^{7-}, but its octet structure seemed to convince them of its stability:

> "An element is 'more' stable if its electron requirements are satisfied, ie: A sodium … one plus ion would be more stable than the usual sodium atom as all its shells contain the full requirements. Figure C [Na^{7-}] is also stable *even though it contains 7 minus ions* [sic] as the valency requirements are satisfied."

> "Both A [Na^{+}] and C [Na^{7-}] have full outer shells and are therefore both stable. *Although C [Na^{7-}] has an extra shell*, it still remains as stable as A [Na^{+}]."

Indeed one student seemed to suggested that the sodium atom would gain seven electrons rather than lose one:

> "With A [Na^{+}] all the electron shells are full so they don't need to react to gain another electron.
> B [Na] is not as stable as C [Na^{7-}] because it *needs another 7 electrons* to fill the outer shell and will react more easily to *gain* electrons.
> C [Na^{7-}] and A [Na^{+}] are equally stable as they both have full outer shells."

Of course Na^{7-} does have an octet or a noble gas electronic structure, but does <u>not</u> have a full outer shell . Indeed one of the students who did <u>not</u> think Na^{7-} was as stable as Na^{+} gave the reason:

> "C [Na^{7-}] is less stable than A [Na^{+}] because C [Na^{7-}] does *not* contain a full outer shell of electrons. ie. 18 whereas A [Na^{+}] does, i.e. 8"

In one case the judgment of stability in terms of octets was reconciled with the learning about ionisation energy, but by failing to associate stability with low energy:

> "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 [Na^{+}] is more stable than B [Na] as it has a full outer shell unlike the atom.
> and C [Na^{7-}] is more stable than B [Na] as it also has a full outer shell

> C [Na^{7-}] & A [Na^{+}] are equally stable - the 7- ion has one more shell & is bigger but are both equally noble and unreactive.”

Here we see that knowledge of stable electronic structures, and ideas about energy changes, are not integrated into a single explanatory framework.

Conclusions regarding student use of the octet rule

To summarise what we have found out about students use of the octet rule. Learners will:

- explain chemical bonding as due to the desires of atoms, rather than due to forces;
- develop a view of the chemical bond that excludes categories such as hydrogen bonding;
- explain chemical reactions in terms of the octet rule, even though the reacting species ‘obey’ the rule as well as the products;
- perceive ions as more stable than atoms, even if they ‘know’ energy is required to ionise the atom;
- perceive highly unstable species as stable if they obey the octet rule.

The thesis presented in this paper is that learners are taught a valuable heuristic at a time when they have no knowledge of why chemical processes occur, and in their efforts to make sense of the subject they develop the heuristic into an explanatory principle, which they proceed to apply in a range of contexts. We can make sense of [*i.e.* we can model] a wide range of unorthodox student conceptions within an alternative framework constructed around the octet rule as an explanatory principle. Further, once this explanatory principle is deeply embedded in their cognitive structure it then acts as a block to learning alternative, more orthodox ways of understanding chemistry.

Presentation of the octet rule

It is certainly not the intention of this paper to suggest that we should completely remove the octet rule from elementary chemistry courses. However, the notion of an epistemological block is intended as an alert that we need to revisit our teaching in the areas where such a block occurs. I am suggesting that the octet rule is the cause of a widespread epistemological learning block among chemistry students. Therefore I recommend we revisit how the rule is presented, and - just as important - in conjunction with what other knowledge. Attention to this point is essential as the lack of any taught explanation of chemical processes means that

- learners will tend to ‘fill in the gaps’
- teachers and authors have to explain chemical ideas without any true explanatory principles to apply.

A selection of elementary text books were examined to see how they present some of these ideas, and the type of language they use. A number of particular points were noticed:

- confusion between octets, full shells and noble gas electronic configurations;
- the octet rule expressed as an explanatory principle, rather than a heuristic device;
- chemical processes explained in anthropomorphic terms;
- the implication that common materials are formed from atomised matter.

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 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 (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 reports 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." 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.*

> Atoms are stable if they have noble gas configurations.
> This is because they have full shells of electrons,
> and a full shell is stable.
> Actually most of the noble gases do not have full outer shells,
> but they behave as if they do,
> because they are stable,
> (and atoms are stable if they have noble gas configurations.
> …)

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 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 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.”
> **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 above.) Once the notion of full shells being stable is established it may be used to explain the ‘purpose’ of bonds,

> “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.

Chemical processes explained in anthropomorphic terms

As the octet rule is only a heuristic for judging the stability of ions and molecules, it does not suggest any mechanism by which octets, full outer shells or noble gas electronic structures might be acquired. In becoming an explanatory principle it takes on teleological or anthropomorphic language.

> "an element requires a stable electron arrangement in its atoms … The outer electron in the sodium atom is readily given to any other atom that needs it."
> **Bethell *et al.*, 1991**, p.54.

> "Hydrogen only has one electron in its outside shell, and needs another to make a stable electron arrangement. Chlorine needs one more electron"
> **Bethell *et al.,* 1991**, p.55.

> "Carbon has four electrons in its outside shell and needs to share four other electrons before it has a stable electron arrangement."
> **Bethell *et al.,* 1991**, p.55.

> "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"
> **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.

> "When two non-metal atoms react together, both of them need to gain electrons, to reach full shells."
> **Gallagher & Ingram, 1989**, p.46.

> "A chlorine atom needs a share in one more electron, to obtain a full shell."
> **Gallagher & Ingram, 1989**, p.46.

> "Each oxygen has only six outer electrons; it needs a share in two more to reach a full shell"
> **Gallagher & Ingram, 1989**, p.46.

> "other atoms try to get this stable arrangement of electrons when they take part in chemical reactions."
> **Holman, 1991**, p.222.

> "When atoms form bonds, they try to get the stable electronic structure of a noble gas."
> **Holman, 1991**, p.224.

> The alkali metals "like to form ions with a 1+ charge"
> **Jarvis *et al.*, 1993**, p.22.

> "Atoms of reactive metals like to form ions. Atoms of unreactive metals like to remain as atoms."
> **Jarvis *et al.*, 1993**, p. 23.

> The halogens "like to form ions with a -1 charge"

> **Jarvis** ***et al.*****, 1993**, p. 47.
>
> "Electrons always try to fill the lowest shells they can."
> **Pople, 1994**, p.47.
>
> "When the very reactive elements come together, the easiest way for them to get the inert gas structure is either to lose or gain an electron."
> **Oxford Science Programme, 1993**, p.23.

It is not clear whether these authors are *deliberately* using language in a metaphorical way, or whether anthropomorphic terms are used due to a tacit understanding that the 'octet rule explanatory principle' does not provide any mechanism to explain these phenomena.

To use terms like 'tend to' and 'tendency' would perhaps make such passages less acceptable to some learners. However I would argue that it would be intellectually more honest, as it converts them from invalid explanation to description. In scientific terms the quotation cited are descriptive - but they are presented as explanation.

As a final example I would like to quote an abridged version of a passage that was presented as 'Annisa's account of electrolysis of lead bromide'. Despite this attempt to disown the prose, the author presents it with no critique (just comprehension questions!)

> "I'm Ernie, I live in the outside shell of a lead atom. There are two of us together in this outside shell, me and my friend Cuthbert… Recently, the atom got really hot [?]… Suddenly, a bromine atom rushed towards us and one of the seven cheerful electrons called out 'Come and join us. We've got room for another in here.' I jumped into their shell. … After a few days it got really hot again, all the electrons in my new home were moving faster all the time … I saw lots of lead particles and believe it or not I saw my old home. I quickly jumped down into the outside shell. … I had a new friend. She said her name was Esmerelda! … "
> **Major, undated**, p.82.

Presumably there is a scientific point in that in a bromine atom the 'seven cheerful electrons' had 'room for another' - *i.e.* the octet rule. To my 'killjoy' ears this point could be lost in the consideration of Ernie's social life. I also have some doubts about hot atoms , and Ernie's ability to recognise his 'old home' (or to happen to come across it - perhaps he should try the National Lottery) and to recognise distinct individual electrons . Perhaps learners will not be confused, and will clearly be able to distinguish the scientific content from the fanciful narrative.

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.

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 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". We 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.) I have previously criticised such an approach as unhelpful in relation to understanding of ionic bonding (**Taber 1993d, 1994a.**) However it 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. **Cooper *et al.*** explain covalent bonding:

> "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.

Perhaps we might suspect 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! 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,

> "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

which shows an isolated carbon atom and four separate hydrogen atoms. Another example is a water molecule formed from an isolated oxygen atom and two separate hydrogen atoms. (**Cooper *et al.,* 1992**, p.55.)

So these strangely irrelevant diagrams cannot be explained as representing real chemical processes, nor as due to some kind of graphical economy. Three possibilities suggest themselves:

> 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, **Watts & Taber, in prep.**) consists of atoms; and materials in our world do need to be derived from such a starting point. As the notion of elemental atoms predates the science of Dalton, Rutherford and Bohr by many centuries this is perhaps not completely fanciful .

If the second possibility were to be correct it would certainly support the notion of the octet rule as an epistemological learning block, 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 status of scientific knowledge

Research evidence suggests that learners may have difficulty accepting the provisional and conjectural nature of scientific knowledge, and the role that theoretical models play in science and science teaching. For example Solomon and coworkers have explored the understanding of 11-14 year old (Key Stage 3) school pupils of the nature of science. Their findings (**Duveen *et al.*, 1993**, pp.26-27) indicate

- some pupils see scientific theories as little more than guesses, whilst other pupils consider theories to be facts or collections of facts;
- experimental results are considered to be unproblematic 'facts';
- "The role of imagination and evidence in theory building and using a model is rarely understood." (p.27.)

Garnett and coworkers comment that

> "A realisation emanating from studies involving student interviews has been the tendency of students to reduce theoretical knowledge and principles to a 'factual' level and 'apply' this in a rote fashion."
> **Garnett *et al.*, 1995**, p.89.

Lederman and O'Malley comment how research has consistently shown that learners at different educational levels "exhibited inadequate understandings of the tentative nature of scientific knowledge" (**Lederman & O'Malley, 1990**, p.226), although their own work suggested that students' written responses could be misleading. In particular interviews demonstrated that although learners might refer to theories being proved, their notion of proof was actually of being 'supported by evidence' rather than anything more absolute. However they found that pupils did not perceive the laboratory as "an effective venue for learning about the tentative nature of science." (p.234.) As **Duveen *et al.*** comment, "Correctly performed experiments and their results become 'theory' for these pupils… There is no room at all for either speculation or explanation in this perspective. It is the most naive form of empiricism." (**Duveen *et al.,* 1993**, p.22.)

Lederman and O'Malley comment that "…science draws its tentative and revisionary characteristics from a complex interaction of its assumptions, methods for developing knowledge, use and development of theories, and the undeniable limitations imposed on all human 'ways of knowing'."(**1990**, pp.225-6.) However, as **Duveen *et al.*** found, learners of science may have a much simpler view of the development of scientific knowledge: "Progress may be attributed entirely to technological improvements." (p.27.)

The role of explanation in student discourse, science teaching and science

Solomon's group also found that "understanding the explanatory nature of theory is often inhibited by lack of clarity about the meaning of 'explain' " (**Duveen *et al.*, 1993**, p.27.) Pupils did not seem to see 'explanation' as the rationale for science (**Solomon *et al.*, 1994**, p.368.) There was found to be a 'lack of differentiation' between 'explanation' and 'description' (p.369) which was considered to be related to the way everyday language uses non-causal 'explanations' (p.370.) This has been noted in the present enquiry into student understanding of chemical bonding - with students giving what have been called 'psuedo-arguments' "a sequence of propositions which has the grammatical structure of an argument, but not the semantic content" (**Taber, 1993a**, p.12.) For the interviewer, the learner's 'explanation' may seem to be "a series of unrelated comments connected with 'because', 'as' and 'therefore' " (p.12.) In one particular case study (**Taber, 1993c**) the co-learner would use the word 'because' in contexts where there was a merely correlational - rather than causal - relationship between phenomena (pp.4-5.)

Although more research is needed in these areas, it seems clear that learners do not generally see scientific theory as developing explanatory schemes that suggest experiments, and interpret empirical results as well as being modified by them. Many learners also fail to appreciate the role of causal explanation in scientific understanding. They will often see the science taught in class less as explanatory schemes and models developed by human ingenuity, than as the way the world is - at least as far as our technology current allows us to tell. For example a model of the structure of the atom may be believed to be based on observations made with very powerful microscopes (**Lederman & O'Malley, 1990**, p.230.)

The potential consequence of such a belief is that the knowledge acquired in this way is imbued with high epistemological status. If the octet rule is learnt in a science class, having been presented with the explicit authority of a teacher, and the tacit authority of science, the learner is likely to accept it as a suitable foundation for understanding her chemistry. If she later finds that this fundamental truth was just a useful way of looking at things, she may have already put too much reliance on it, and invested too much effort into constructing knowledge on its foundations.

Tajinder was a student who expressed this frustration quite clearly during a research interview (see the box below.) At A level Tajinder was quite able to appreciate different models, but had to overcome the initial block of having already learnt what he had thought was “the truth”. Tajinder soon accepted that it was normal in science to try out different explanations based on various theories and models: “there’s loads of things in chemistry like that.” His perception of elementary science classes is probably not unusual. One of **Lederman & O’Malley**’s interviewees looked back from high school (where many viewpoints were discussed), to middle school science where they had “just studied the way things were” (**1990**, p.234.)

Suggestions for changing the teaching of chemistry

Perhaps if we put more emphasis on electrostatics in elementary courses the octet rule would not be misapplied in the way discussed in this paper? A principle for explaining chemical reactions could be taught along simplified lines:

- substances react when their atoms interact;
- atoms interact because the charged particles on adjacent atoms effect each other
- sometimes the negative electrons become attached to two atoms due to the attraction of the nuclei - this acts as a bond to hold the atoms together
- sometimes the negative electron of one atom is so strongly attracted by another atom that it is transferred - this results in positive and negative ions which are then attracted together

Subsequently, once this principle is well established, the octet rule could then be introduced as a means of identifying ions and molecules most likely to be stable. Although this ‘introductory electrostatic principle’ may seen abstract and arbitrary to many learners, it is surely no more so than the octet rule principle? The starting point above is able to be developed later to include polar bonding, hydrogen bonding *etc*., in a way that is not possible with the octet rule.

Perhaps just as important is our general approach to teaching the models and theories of science at elementary level. If learners are taught to appreciate our science in this manner, rather than as ‘truth’ or ‘the way things are’, then prior learning has less likelihood of becoming an epistemological block.

References:

Andersson, A. (1986) The experiential gestalt of causation: a common core to pupils’ preconceptions in science. **European Journal of Science Education**, 8 (2) pp.155-172.

Ausubel, David P., & Floyd G. Robinson, **School Learning: An Introduction to Educational Psychology**, London: Holt International Edition, 1971 (first published by Holt, Rinehart and Winston, 1969.)

Ben-Zvi, Ruth, Bat-Sheva Eylon & Judith Silberstein, Is an Atom of Copper Malleable?, **Journal of Chemical Education**, 63 (1), January 1986, pp.64-66.

Bethell, George, David Coppock & Lynne Pebworth, **Integrated Science 2**, Oxford: Oxford University Press, 1991

Black, Paul J., & Arthur M. Lucas, **Children’s Informal Ideas in Science**, London: Routledge, 1993

Carmichael, Patrick, Rosalind Driver, Brian Holding, Isabel Phillips, Daryll Twigger and Mike Watts, **Research on students' conceptions in science: a bibliography**, Children's Learning in Science Research Group, Centre for Studies in Science and Mathematics Education, University of Leeds, 1990 (plus addenda, 1991, 1992).

Audrey B. Champagne, Richard F. Gunstone & Leopold E. Klopfer, Effecting changes in cognitive structure among physics students, Chapter 11, in **West & Pines, 1985**, pp.163-187.

Cooper, Stab, Will Deloughry, Mike Hiscock & Philip Naylor, **Complete Coordinated Science: Chemistry**, Oxford: Heinemann Educational, 1992.

Driver, Rosalind, Ann Squires, Peter Rushworth and Valerie Wood-Robinson, **Making Sense of Secondary Science: research into children's ideas**, London: Routledge, 1994.

Duit, R., Students' conceptual frameworks: consequences for learning science, Chapter 4 in Glynn, S. M., Yeany, R. H. & Britton, B. K., **The Psychology of Learning Science**, Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1991, pp.65-85.

Duveen, Jonathan, Linda Scott and Joan Solomon**,** Pupils' understanding of science: description of experiments or 'A passion to explain'?, **School Science Review**, **75** (271), December 1993, pp.19-27.

Furnham, Adrian, Lay understanding of science: young people and adults' ideas of scientific concepts, **Studies in Science Education**, **20**, 1992, pp.29-64.

Gallagher, RoseMarie & Paul Ingram, **Coordinated Science Chemistry**, Oxford: Oxford University Press, 1989

Garnett, Patrick J., Pamela J. Garnett and Mark W. Hackling, Students' alternative conceptions in chemistry: A review of research and implication for teaching and learning, **Studies in Science Education**, **25**, 1995, pp.69-95.

Gelman, S. A. & Markman, E. M., Categories and induction in young children, **Cognition**, **23**, 1986, pp.183-209.

Gilbert, John K., & Arden Zylbersztajn, A conceptual framework for science education: The case study of force and movement, **European Journal of Science Education**, **7** (2), 1985, pp.107-120.

Holman, John, **The Material World** (Nelson Balanced Science), Walton-on-Thames: Thomas Nelson and Sons, 1991.

The **Hutchinson Dictionary of Science**, edited by Peter Lafferty and Julian Rowe, Oxford: Helicon Publishing Ltd., first published 1993, revised and updated, 1994.

Jarvis, Alan, with David Appleby, Ray Jardine and Chris Thomson, **Action Science: Particle patterns**, Oxford: Oxford University Press.

Major, Janet, **Materials**, University of Bath Science 5-16, Key Stage 4, undated.

Oxford Science Programme, Paul Denley (Consultant Ed.), Stephen Pople (Managing Ed.), book R**, Materials and models,** Oxford: Oxford University Press, 1993

Pope, Maureen & Pam Denicolo, Intuitive theories - a researcher's dilemma: some practical methodological implications, **British Educational Research Journal**, **12** (2), 1986, pp.153-166.

Pople, Stephen, **Science to 14** (KS3 Summary Book), Oxford: Oxford University Press, 1994.

Russell, Bertrand, **A History of Western Philosophy** (2nd Ed.), London: George Allen & Unwin, 1961.

Solomon, Joan, Jon Duveen & Linda Scott, Pupils' images of scientific epistemology, **International Journal of Science Education**, **16** (3), 1994, pp.361-373.

Taber, Keith S., Student conceptions of chemical bonding: using interviews to follow the development of A level students' thinking, paper presented to the Conference on On-going Research, '**Facets of Education - Dimensions of Research**', Institute of Educational Research and Development, 24.6.93, University of Surrey. (1993a)

Taber, Keith S., Stability and lability in student conceptions: some evidence from a case study, paper to the symposium '**Science Education - Teacher Education**', British Educational Research Association Annual Conference, Liverpool, September 1993. (1993b)

Taber, Keith S., Annie: Case study of an A level student's understanding of chemical bonding, paper to the symposium '**Science Education - Teacher Education**', British Educational Research Association Annual Conference, Liverpool, September 1993. (1993c)

Taber, Keith S., Understanding the ionic bond: student misconceptions and implications for further learning, paper presented to the symposium '**Research and Assessment in Chemical Education**' (22.09.93) at the Royal Society of Chemistry Autumn Meeting, Warwick, 21-23.09.93. Reprinted in Research in Assessment XII: **Science Ain't Easy - Difficulties and misconceptions in chemistry and science**, London: The Royal Society of Chemistry Education Division, 1995, pp.48-63. (1993d)

Taber, Keith S., Examples of Student Comments about Chemical Bonding, poster presented to the symposium '**Research and Assessment in Chemical Education**' (22.09.93) at the Royal Society of Chemistry Autumn Meeting, Warwick, 21-23.09.93. Reprinted in Research in Assessment XII: **Science Ain't Easy - Difficulties and misconceptions in chemistry and science**, London: The Royal Society of Chemistry Education Division, 1995, pp. 64-73. (1993e)

Taber, Keith S., Misunderstanding the Ionic Bond, **Education in Chemistry**, **31** (4), July 1994, pp.100-103. (1994a)

Taber, Keith S., "The teacher-researcher's duty: accounting for ourselves to our co-learners", paper presented at 'Accounting for Ourselves', **World Congress 3: Action Learning, Action Research and Process Management**, University of Bath, July, 1994. (An abridged version of this paper is published in the proceedings, edited by Laidlaw, M., Lomax, P. & Whitehead, J., pp.230-233.) (1994b)

Taber, Keith S., Can Kelly's triads be used to elicit aspects of chemistry students' conceptual frameworks?, paper presented to the 20th **British Educational Research Association** Conference, University of Oxford, September 1994, pp.35-36. (1994c)

Taber, Keith S., Time to be definitive?, **Education in Chemistry**, **32** (2), March, 1995, p.56. (1995a)

Taber, Keith S., An analogy for discussing progression in learning chemistry, **School Science Review**, **76** (276), March 1995, pp.91-95. (1995b)

Taber, Keith S., The octet rule: a pint in a quart pot?, **Education in Chemistry**, **32** (3), May 1995. (1995c)

Taber, Keith S., Development of Student Understanding: A Case Study of Stability and Lability in Cognitive Structure, **Research in Science & Technological Education**, **13** (1), 1995d, pp.87-97. (1995d)

Taber, Keith S., The Truth about Ionic Bonding?, research report, January, 1995, available from the author. (1995e)

Taber, Keith S., Chlorine is an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A level chemistry class, in preparation.

Taber, Keith S. & Mike Watts, Constructivism and concept learning in chemistry - perspectives from a case study a paper to the theme of **Studies on the Process of Learning Chemistry** presented at the 3rd European Conference on Research in Chemical Education held at Lubin and Kaimierz, Poland 25th - 29th September, 1995.

Taber, Keith S. & Watts, Mike, The secret life of the chemical bond: students' anthropomorphic and animistic references to bonding, **International Journal of Science Education**, in press.

Taber, Keith S. & Watts, Mike, A pragmatic framework for discussing learners' ideas in science (working title), in preparation.

Watts, Mike, and Keith S. Taber, An explanatory gestalt of essence: students' conceptions of the 'natural' in physical phenomena, in preparation.

White, Richard T, Interview protocols and dimensions of cognitive structure, chapter 4 of West, Leo H. T., and A. Leon Pines (Eds.), **Cognitive Structure and Conceptual Change**, London: Academic Press Inc., 1985, pp.51. -59.