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Mediating mental models of metals:

acknowledging the priority of the learner's prior learning.

Keith S. Taber

Abstract:

This paper describes the conceptualisations, or mental models, of the nature of the bonding and structure of metals of a group of UK college students. It is suggested that these mental models may be understood in terms of the students' prior learning about covalent and ionic bonding, and the prevalence of a common alternative conceptual framework for chemical bonding labelled 'the octet framework'. This study illustrates the prominence of prior learning in channelling the interpretation of subsequent teaching, and highlights the significance of the decisions made by curriculum planners, textbook authors and teachers on the order of presenting subject content; the degree of simplification of scientific models; and the selection and presentation of metaphors.

Introduction. Find out what your pupil knows and teach accordingly - the importance of prior learning

This paper will discuss the mental models revealed when UK college students (c.16-19 year olds) were asked to describe and explain the bonding in metals. It is suggested that this data provides very powerful evidence of how learners' developing mental models are strongly influenced by their prior learning. The role of previous teaching, and particularly of a common and influential alternative conceptual framework, will be shown to channel students thinking, and to sometimes act as an impediment to effective learning of the scientific model.

The psychologist David Ausubel is well known for championing the difference between 'meaningful' and 'rote' learning (e.g. Ausubel & Robinson, 1971), where meaningful learning occurs when the learner can relate new information to that already held in 'cognitive structure'. Ausubel emphasised his view of the importance of prior learning in his advice that the most important thing for teachers to do was *to ascertain what the learner already knew - and to teach 'accordingly'*. Put another way,

> "the most important factor influencing the meaningful learning of any new idea is the state of the individual's cognitive structure at the time of learning...if new material is to be learned meaningfully there must exist ideas in cognitive structure to which this material can be related" (Ausubel & Robinson, 1971, p.143)

This is certainly one of the key tenets of the constructivist movement in science teaching (Driver, 1989) which developed from a series of key publications in the early 1980s (Driver, 1983; Driver & Erickson, 1983; Driver, Guesne & Tiberghien, 1985; Gilbert, Osborne & Fensham, 1982; Gilbert & Swift, 1985; Gilbert & Watts, 1983; Osborne, Bell & Gilbert, 1983; Osborne & Freyberg, 1985; Osborne & Wittrock, 1983; Pope & Gilbert, 1983). This research programme emphasised the importance of exploring the learner's existing ideas to inform teaching, and has led to an immense effort to catalogue learners' ideas in many science topics at various ages (e.g. Driver et al., 1994). Whilst this research programme has drawn upon the work of a range of psychologists for its theoretical base (e.g. Piaget, Vygotsky, Kelly, Bruner: see Taber, 2000a), Ausubel's succinct formulation can almost be considered a slogan for this research (Duit, 1991).

Constructivist theory suggests that *meaningful* learning can only take place when the learner is able to relate the information provided by a teacher to their existing knowledge. Cognitive structure (the learner's existing knowledge structure) provides the only available interpretative framework for making sense of new information. So the learner's existing knowledge acts (according to various metaphors) as the bedrock on which new learning is 'anchored' (Ausubel), glasses through which teaching is seen (Pope & Watts, 1998), the foundations upon which new knowledge may be built, or - to use a scientific analogy - the substrate for new learning (Taber 2002).

Effective teaching, then, requires the teacher to be familiar with the learners' personal knowledge structures as well as the formal public structure of scientific knowledge. In actuality, at school level, this will more correctly be the curriculum models of science, which have already been re-interpreted by curriculum planners, text-book authors and teachers to provide a version of the science intended to be suitable for the learner's stage of development (Gilbert, Osborne, & Fensham, 1982). Such curriculum models *should* present versions of science which are at an optimum level of simplification (Taber 2000b), simple enough to make sense, but not oversimplified such that they may block further progression in understanding. In practice this may not always be the case (e.g. Justi & Gilbert, 2000).

There are clearly several ways that the intended match between the learner's prior knowledge and the teacher's presentation can go wrong. The teacher should be aware of the prior learning to be expected of learners at a particular level: but in practice the assumed prior knowledge may be missing, or may include alternative conceptions, or the learner may simply fail to 'make the connection' intended by the teacher (Taber 2001a). Thus the importance of Ausubel's advice: teachers need to be constantly exploring the learner's interpretations and understandings.

This paper describes the mental models of learners developing an understanding of metallic bonding. It will be suggested that this study can be interpreted largely in terms of *the learners trying to make sense of a new category of chemical bonding in terms of their prior learning*.

Scientific and curriculum models of metallic bonding

The structure of metals, and the nature of bonding in metals, are complex phenomena (Duffy, 1990; Greig, 1969; Murrell et al., 1985; Pauling, 1960), and it would not be appropriate to present the most detailed scientific models available in school science or college (high school) level chemistry. In teaching science we present curriculum models which are designed to be matched to level of complexity and abstraction that students can most benefit from.

Good teaching models therefore have to take into account both the level of *cognitive* development of the students (cf. Shayer & Adey, 1981) and the relevant *conceptual* development - that is the extent of the prior knowledge about the topic available to act as the foundations of new knowledge.

In order to give such a match between curriculum and students it is necessary to simplify the science that is taught. However, there is little point in simplifying a topic to such a degree that the curriculum model lacks any scientific validity. Attempts to reduce the complexity of a topic may actually make it more difficult for students to see the logic of the science and make sense of why new scientific ideas were proposed (Justi & Gilbert, 2000; Niaz, 1998), and some simplifications may actually encourage students to develop alternative conceptions that will need to be challenged later (Taber, 2000b).

A balance is therefore needed between maintaining the authenticity of the science taught, and ensuring the ideas are accessible to the students. The 'optimum level of simplification' is enough simplification to allow students to understand and learn about the topic, yet also enough rigour to provide a basis for students to develop further more advanced models later in their studies (Taber, 2000b, 2002a).

In college level chemistry in the UK system (e.g. General Certificate of Education Advanced level), the target knowledge for metallic bonding would include the following features (Andrew & Rispoli, 1999; Atkins, et al., 1988; Clugston & Flemming, 2000; Fullick & Fullick, 1994; Hill & Holman, 1995; Lewis & Berry, 2000):

- students should recognise that (solid) metals comprise of positive atomic cores (cations) arranged in a regular three-dimensional array (lattice) and outer shell electrons that are delocalised across the lattice;
- students should appreciate that the cores attract, and are attracted by the delocalised (free/conduction/valence) electrons, and this binds the structure together;
- students should appreciate that there are also repulsions present (between cores, between electrons), and that the metallic structure is stable because it is an equilibrium structure where the attractions and repulsions balance;
- students should understand that the electronic structure of atoms can be described in terms of atomic orbitals, and that when atoms 'overlap' their atomic orbitals they form molecular orbitals: in metals this process produces delocalised molecular orbitals which the valence electrons occupy.

Now clearly there is the potential to develop this model much further, to consider - for example - the electronic band structure in metals compared with insulators and semi-conductors, however this would not be expected at this level. This target knowledge does not specify this level of detail or sophistication, but it does provide a suitable basis for developing such ideas for those students who may need to study the topic in more detail in higher education.

The key feature of this target knowledge is that metals are structures bonded together in regular arrays such that each atomic centre is bonded to those around it, and that bonding can be explained in terms of the forces between the charged components of the lattice - the cations and free electrons.

Learners' ideas about metallic structure and bonding

The literature of science education includes a number of terms for describing aspects of learners' ideas, such as misconceptions, alternative frameworks and so forth, and different authors do not always use these terms in equivalent ways (Abimbola, 1988). The present paper considers aspects of students' thinking about the 'molecular level' structure of metals, and what will be described is a series of mental models (Greca & Moreira, 2000; Nersessian, 1992) identified from a study of college students' developing understanding of chemical bonding.

Chemical bonding has long been recognised as a key concept area (e.g. Fensham, 1975), and learners' ideas about bonding have attracted researchers' attention (e.g. Barker & Millar, 2000; Harrison & Treagust, 2000; Peterson, Treagust & Garnett, 1986; Taber, 1997a; Tan & Treagust 1999; van Hoeve-Brouwer, 1996). However, much of this attention has been focused on understanding of covalent and ionic bonding, and there is a limited amount of evidence about how students conceptualise metallic bonding.

Student knowledge of the structure of metals is often restricted by a limited understanding of the molecular model of matter. There are reports in the literature of students believing that atoms in a metal are hard, but those in liquids are softer (Harrison & Treagust, 1996); or that copper is malleable because it has malleable molecules (Ben-Zvi et al., 1986); or that light passes through glass but not metals because the molecules (sic) are closer together in metals than glass (de Posada, 1997).

Taber (1997a, 2001c) reported that U.K. students starting out on a college chemistry course tended to present four notions of the bonding in metals:

- there is no bonding in metals;
- there is some form of bonding in metals, but not proper bonding;
- metals have covalent and/or ionic bonding;
- metals have metallic bonding, which is a sea of electrons.

(These ideas will be discussed in more detail in the present paper.)

Each of these categories has some support from other studies. The idea that metals are molecular has also been reported by several other authors (Fleming, 1994; de Posada, 1997; Harrison & Treagust, 2000; Coll & Taylor, 2001). The notion that metallic bonding is considered a 'lesser' form of bonding has also been reported by Coll and Taylor (2001).

These latter authors have reported on the mental models for chemical bonding used by secondary, undergraduate and post-graduate students from Australia and New Zealand (Coll & Taylor, 2002). They found that the 'sea of electrons' model was a preferred model at all three levels. However they also reported some secondary level students attempting to apply a model based on the octet rule, and some learners at all three levels apparently having only the vaguest of ideas about metallic bonding. One of the post-graduate chemists they interviewed admitted to not thinking of metals as being bonded.

The research context: studying learning pathways

This present paper discusses data collected during a project to explore students developing understanding of the concept of chemical bonding. The students were attending a U.K. college studying an 'Advanced level' course: i.e. a course at university entrance level normally taken over two years after the school-leaving age of sixteen. Although the students were studying in the same college and being taught by the same teachers, they had previously been taught science in a range of local schools.

As suggested above, there has been a vast amount of research into learners' ideas about scientific topics, but much of this has elicited learners' conceptions at a single time. It has long been recognised that this mode of research has limited potential (e.g. Black, 1989; Watts, 1988).

In recent years there has been a move toward studies which explore in detail how learners' ideas develop over extended periods of time. These studies report 'conceptual trajectories' or 'learning pathways' (e.g. Harrison and Treagust, 2000; Johnson, 1998; Petri & Niedderer, 1998; Scott, 1992).

The research project from which the present study derives was of this type. Students were interviewed over a period of many months (mostly over the full length of their two year course), and also provided data in the form of Kelly's repertory test, diagrams, concept maps, answers to test question etc. (Taber, 1997a). Fifteen students were involved in the interview study, and they are referred to by assumed names later in this paper. The interviewer was the present author, who was teaching the students at that time (Taber, 2000b). A grounded theory approach (Glaser, 1978; Glaser & Strauss, 1967; Strauss & Corbin, 1998) was used (described in Taber, 2000c) to develop detailed case studies (Taber, 1995, 2000d, 2001b), which were then used as the basis for developing more general models of progression in student thinking (Taber, 1999a).

Although the research sessions were not intended to teach, the students who were interviewed not only found that the sessions allowed them to gauge their progress and identify areas where their explanations were weak, but also that the actual process of being made to think about their learning helped them clarify and so develop their thinking about the science (Taber, 2002b, cf. Caravita & Halldén, 1994; Garnett, Garnett, & Hackling, 1995; Petri & Niedderer, 1998; Vosniadou, 1992, 1994).

As part of the grounded theory approach (Taber, 2000c) supporting data were collected from a wider range of students (for example, from college tests) and some examples are included in the results reported below.

Developing understanding of chemical bonding: a review of findings from the research project

The main trend observed in the research was a shift towards an understanding of chemical bonding in terms of electrical forces (which would be considered a 'target' model) and away from an alternative way of thinking, labelled the octet framework (to be described below), that tended to predominate at the start of the course (Taber, 1999a). Students varied considerably in the extent to which their thinking developed in this way, and even for those who made considerable progress the shift was not completed during the two year course (Taber 2001b). Similarly, students varied in the extent to which they integrated ideas about electrical forces with notions about bonding having to do with minimising energy (e.g see Taber 2000d) and in the extent to which they took up quantum ideas and so started to think of bonding in orbital terms (Taber, 2002c, d).

One of the key findings of the study was the identification of an alternative conceptual framework to explain many aspects of different learners' ideas about chemical bonding. This was labelled the 'octet' framework (Taber, 1998, 1999b). All of the students interviewed began their course using some aspects of this framework, and most continued to draw on it heavily throughout their course. The students tended to think first of the models they developed whilst studying school science, even when they had more sophisticated and scientifically valid ideas available - something that has also been found by Coll when interviewing chemistry graduates (Taber & Coll, 2002).

It should be pointed out that the alternative conceptual framework presented in the literature is not intended to precisely represent part of the cognitive structure of all, or indeed any, of the students interviewed: but rather is the researcher's model representing many common themes (Taber, 1998). This proviso notwithstanding, certain key aspects of the framework were represented in the comments of nearly all of the students interviewed, and were also reflected in additional data collected as part of the process of developing grounded theory (see Taber, 2000c).

The octet framework was so called because it clearly has its *origins* in the octet rule for predicting the valencies of elements, (and so the charge on common ions and the stoichiometries of many compounds). For example, using this rule the student should predict that the common magnesium ion is the Mg^{2+} ion, and that the stable hydride of nitrogen (ammonia) will have the formula NH_3. This rule works because in most common stable ions and molecules species mimic the electronic structures of the noble gases (2, 2.8, 2.8.8 etc.).

I choose to use the term 'mimic' here, because these similarities, whilst striking, are in some ways superficial. For example: in a water molecule we might suggest that hydrogen and oxygen atoms have acquired the electronic configurations of helium and neon, and a simple 'dot and cross' type representation would seem to show this. If we make a more detailed analysis of structure in terms of electron orbitals, however, it is clear that the electronic arrangement in the molecule is in important ways different to that in the atoms (e.g., Murrell et al., 1985). In an important sense there are no atoms in water molecules. Molecules are different configurations of nuclei (or atomic cores) and electrons to the group of atoms from which we sometimes say they comprise. In chemical terms it is just as incorrect to say that a water molecule *contains* atoms of oxygen and hydrogen, as to claim that the substance water contains the substances hydrogen and oxygen (Taber, 2003).

This point may seem laboured but it is very important for two reasons. Firstly, I wish to clearly distinguish between the octet rule itself, which is a very useful heuristic when used within its range of application, and the alternative conceptual framework labelled the octet framework, which can act as a substantial learning impediment (Taber, 2001a).

Secondly, there is evidence that convenient habits of thinking and talking which expert chemists and experienced science teachers are able to use for personal reflection or communication among themselves (because we know exactly what we do and do not mean by saying a molecule contains atoms) are often acquired by learners as absolute and literal meanings rather than being recognised as short-hand (Taber, 2003). So, for example, scientists (and teachers) will use anthropomorphic language to describe aspects of the molecular realm and may believe that such talk will be understood metaphorically. Yet even quite advanced learners (e.g. 16-19 year olds) sometimes try to interpret such talk literally (Taber & Watts, 1996).

The octet framework

When students were interviewed at the start of the Advanced level chemistry course (i.e. c.16 years of age) it became clear that the octet rule had been inappropriately adopted as the basis of a wide ranging explanatory principle for making sense of bonding and chemical reactions. The octet framework has been described and illustrated elsewhere (Taber, 1998) so the presentation here will be restricted to sufficient detail to support the argument made later in this paper.

When asked about chemical reactions or bonding, students were found to commonly begin by thinking of the reactants in terms of isolated atoms. They explained the reactions in terms of the atoms *wanting* or *needing* to get full shells: the atoms would form bonds so that they would get the number of electrons that they 'needed'.

Students believed there were two ways that atoms could achieve full shells, and so two forms of chemical bond - sharing (covalent bonding) and electron transfer (ionic bonding). It should be noted that it was common for ionic bonding to be *identified and equated* with the process of electron transfer to form a pair of ions which were then considered bonded *because of* that process.

From this perspective a sodium ion can only be ionically bonded to one other chloride ion. This leads to considering NaCl to be a pseudo-molecular material with bonded ion pairs (Taber, 1994, 1997b, cf. Butts & Smith, 1987). Each ion has one chemical bond, plus five weaker interactions with other ions. (These other interactions are said to be weaker because they are considered to be 'just' based on electrical forces, and not on the electron transfer process equated with the ionic bond!)

The octet framework was found to be well established by age 16, and to be tenacious enough to seriously impede the learning of important new ideas presented in the college curriculum. It has been found that even giving students questions including the *molecular* formulae of reactants does not prevent them explaining a reaction in terms of the need of the atoms: so hydrogen and fluorine (H_2 + F_2) are said to react to allow *the atoms* to fill their shells. When students were asked about the ionic bonds in precipitates formed by 'double decomposition' they still assumed that electrons had been transferred *between the ions in the precipitate* (as this was their criterion for ionic bonding), even though they 'knew' those ions were already present in the reaction mixture (Taber, 2002a).

Covalent bonding is defined by many students as electron 'sharing', a term which often seems intended to reflect its social meaning and so imply 'equally'. Students conceptualising the bond in this way have difficulty making sense of polar bonds. On bond fission atoms are assumed to take 'their own' electrons back (so heterolytic bond fission can not be fitted into the scheme). Dative bonding is often another mystery (as there is no incentive for the donor atom to share electrons that are already part of an octet) and electron deficient compounds and the 'expansion of the octet' in the third period (e.g. PCl_5, SF_6) can not be explained by students operating with this conceptual framework.

Students using the octet scheme may also make other incorrect deductions: suggesting that magnesium can only undergo two successive ionisations (as it then has a full outer shell), and even that the Na^{7-} *anion* will be stable because of its octet structure (Taber, 2002a). Intermolecular bonding is often not considered to 'count' as a type of chemical bonding because it does not help atoms achieve full shells. When first learning about hydrogen bonding some students just assume this is nothing more than covalent bonding involving hydrogen. If this assumption becomes untenable, then hydrogen bonding tends to be seen as something less than 'proper' bonding. A proper bond is considered as one that allows an atom to obtain a full shell or octet of electrons: this means it is either covalent or ionic.

The mode of reporting of learners' ideas in this study

The interviews in the UK study mostly used a simple semi-structured protocol based around a series of basic line diagrams (i.e. interview-about-instances, Gilbert, Watts & Osborne, 1985), such as that reproduced here as figure 1. Questions such as 'what do you think is shown in the diagram', and 'is there any bonding in the substance/species shown' were supplemented according to student responses (Taber 1997a). Most of the interviews lasted **over** 30 minutes, and many over an hour.

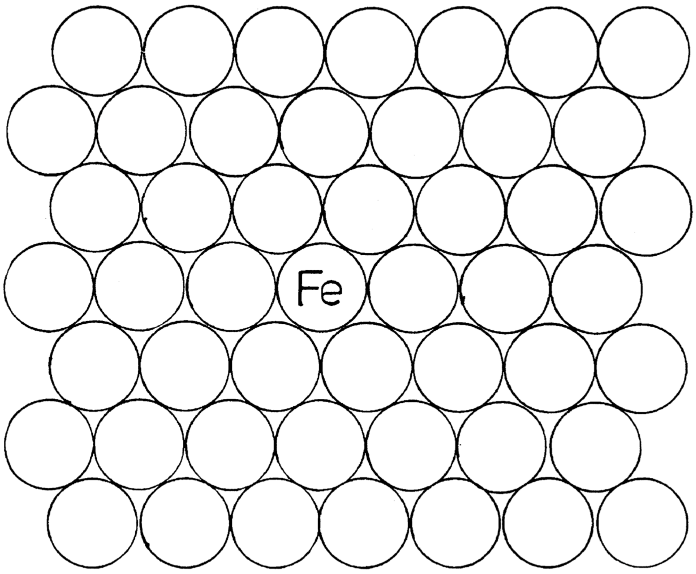

Figure 1. A representation of metallic iron.

In the present paper an attempt has been made to sequence and juxtapose data from the study to illustrate the particular findings discussed here, i.e. that these students' mental models of metallic bonding present a strong example of how *prior learning can be a major determinant of the learners' interpretations of subsequent teaching*.

A researcher always has to be selective in presenting data in a suitable form for publication (not to provide too much detail to overwhelm readers), yet has to attempt not to over-simplify complex phenomena (Pope & Denicolo, 1986). In a detailed study the same data may tell several 'stories'. In order to explore the progression of a learner's ideas in detail it is necessary to collect together data from a single learner, paying particular heed to the temporal sequence in which data was collected (e.g. Taber, 1995).

One of the informants in the present study was interviewed on over twenty occasions leading to a considerable database on his case. This detailed case study provided evidence to illustrate how an individual learner may concurrently hold a range of alternative models (or manifold conceptions) to explain the same phenomena (Taber 2000d, cf. Harrison & Treagust, 2000) and to explain how the notion of a conceptual ecology could be used to explain the shifts in his 'profile' for selecting from these alternatives (Taber, 2001b cf. Mortimer, 1995). The different purposes of the two papers describing this particular case informed the selection and arrangement of evidence in those reports.

In the present paper, as in others deriving from this research project, the author has attempted to construct *a narrative* to persuade the reader of the merits of the specific argument being made, whilst still presenting an authentic account of the research findings. As the reader should always be alert to an author's possible bias, it is considered good practice to be explicit about this process (as clearly the selection and sequencing of material provide much scope for the operation of any bias). In this present paper, then, material is presented thematically, rather than data from each learner being presented separately and in a strict temporal sequence. This loses much of the sense of progression in the thinking of the individual students discussed; but allows the researcher to provide the reader with an overall structure to the data presented.

Characterising learners' conceptualisations of metallic bonding

1. there is no bonding in metals

When students were shown a representation of iron particles in a lattice arrangement, similar to that in many school and college level texts (see figure 1), some did not think the substance represented would have any bonding. The type of diagram shown did not *explicitly* represent any bonding, and when Kabul was shown the figure he commented that "there *should* be bonding but it doesn't look like it".

Other students did not realise that there would *need* to be any bonding to make the particles stay in the lattice arrangement. Annie thought that the circles in figure 1 were "iron atoms within an element...all close together", which hold together *because* "they're all the same sort". So, according to Annie, "they're all the same and don't need to be bonded". Similarly, Jagdish, explained that there was no bonding in the iron represented in figure 1 as it was "just a lot of iron atoms" which "just formed like this" and would stick together without needing to be bonded.

2. there is some form of interaction in metals, but not proper bonding

Even when students *were* aware that some specific type of interaction would be needed to keep the particles in position, they did not necessarily recognise this as a form of chemical bonding.

So Noor recognised figure 1 as "an arrangement of atoms, iron atoms", but she did not think any bonding was represented. Noor thought "there must be something", i.e. an interaction between the iron atoms, although she did not "think there's any chemical bonding". Noor was familiar with two classes of chemical bond, covalent and ionic, and did not believe either type was involved in holding the iron atoms together. She did not think there were any other types of bonding possible.

As reported in the previous section, Annie did not think there was any bonding in iron at the start of her college course. By the end of her two year course she had come to accept that something was responsible for the integrity of the structure (and she had been taught about metallic bonding): but she was still reluctant to accept this as amounting to real bonds. Annie thought that, "you haven't got *like actual bonds* in metallic bonding". By 'actual bonds', she appeared to mean something that she could recognise as either covalent or ionic, "there's still bonds, but, not in the sense of like *covalent or ionic* bond, you're not getting electrons *completely transferred or shared*, between the two. It's not as definite".

Annie's comments seem to imply that she considered the type of bonding in metals as somehow inherently a *lesser* type of bonding, as, "the atoms, are sort of held by metallic bonds, although basically the bonds are *just* sort of holding them altogether, *rather than combining them to form something*". Annie appeared to be attempting to understand the metallic bond in terms of the more familiar categories of covalent and ionic bonds. So she thought that the metallic bonds are "sort of *like ionic* in a way, 'cause one metal sort of donates to another, but it occurs in metals and it won't occur between … a p-block [element] and an s-block [element]". However,

> "they're not sort of *really sharing*. And they're not *really combining*, because you're not making sort of a separate molecule, so although they are sort of like all held together, there is something going on, although it's not really, *you can't really class it as ionic bonding or covalent*"

3. metals have covalent bonding

Those students who recognised the need for some form of chemical bond to hold metals together at the start of their course were often only aware of two types of bond (i.e. covalent and ionic). So in Carol's first interview, she argued that there had to be bonding in a metal. She explained that there had to be some form of bond in iron,

> "or it wouldn't be held together, would it? I reckon, if they didn't have any bonds then the circles would be spread out, and it would be like, liquid or something? I reckon it's a solid because they're close together, and it's closely packed, and it looks as though it could be in a kind of lattice, and that's what solids are, in a lattice"

In the absence of a category of metallic bond Carol suggested that these bonds in a metal would be "covalent".

Such comments were reflected in the responses to written tests of other students in the college:

> "In metal the electron are Covalently bonded."

> "Copper:- has bonding of covalent character as it is a stable metal."

In Mike's first interview he suggested that figure 1 showed "a block of iron atoms joined together", where he thought the bonding "would be covalent bonding". He explained (in his terms) how between the iron atoms "there would be an attraction in as much that they're balancing out their outer shields [i.e., shells] of electrons so they have eight",

> "if an atom has, say, six electrons in [its] outer shield, it would need two more electrons from another substance to balance, make it up to an eight. So another atom's got to share two extra electrons, to build up the outer shield."

From figure 1 Mike deduced that iron needed six electrons to fill up its outer shell. Mike appeared to be interpreting the geometry of the figure (showing one layer in a close packed structure) as implying the valency of the species. Mike's classmate Kabul drew similar inferences about the bonding.

4. metals have bonding similar to covalent bonding

Near the start of his course Kabul thought that "probably" the atoms in iron (in figure 1) would "stick together". He thought there must be some sort of force attracting the atoms together, but he had not "heard the name". The bonding was "different" to covalent and ionic, and Kabul suggested that "it's probably metallic bonding", but claimed this was just a term he had invented for the type of bonding "probably found in metals". He actually had "no idea" what this metallic bonding might be. Later in the term Kabul drew an example of metallic bonding (figure 2), although his diagram did not give any clear indication of what this type of bond was.

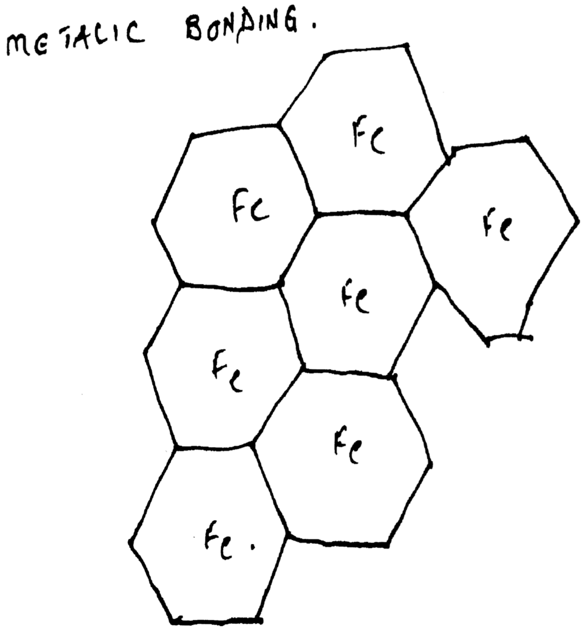

Figure 2. Kabul's representation of metallic bonding.

Kabul had "just read-up it was a hexagon. Iron forms a hexagon around it's shell, you know, metallic bonding". Kabul appeared to have developed a hypothesis about the nature of the hexagon, that "iron has got two electrons in this s-shell, and four [sic] electrons in its d-shell". The lines of the hexagon in Kabul's diagram meant "it has got six electrons in its outermost [sic] shell, which are bonded to other electrons of the metal". Kabul was able to suggest how he would extend this formalism for other metals. "depend[ing] on how many electrons" the atom had in its outer shell. So, according to Kabul, this would be "a decagon" for zinc, a "pentagon" for manganese, a "tetrahedral shape" for chromium, "probably a triangle" for vanadium, "just two lines" for titanium and "just a single line" for scandium. Kabul did not extend this approach to the s-block elements potassium and calcium where he would "just draw circles. With just a 'plus', and 'two-plus' in between".

In the same interview Kabul explained the structure of cobalt as giant molecular, by which he meant it was "a macromolecule…in which there are strong covalent bonds". Kabul *also* suggested that cobalt would have "strong *metallic* bonds", but he still thought cobalt could have a giant molecular structure as in cobalt "strong covalent bonds exist *between the molecules*".

At the end of his first year of the course Kabul was still not prepared to suggest any further details of what metallic bonding might be, beyond such tautologies as "metallic bonding occurs in metals", and "it's just bonding between metal atoms". It is interesting to note in this context that he *was* able to describe how the force between atoms was "the force from the nucleus…The nucleus of iron tends to attract electrons from the nucleus of other iron atoms". By the end of his two year course Kabul referred to metallic bonding as being "*similar to covalent* bonding", in that their "outermost…electron shells, they overlap with one another and they become attracted".

5. metals have ionic bonding

At one point near the end of her course Annie suggested that sodium was "held together by *ionic bonds*, within the lattice". Another student interviewed, Paminder, had suggested that there might be ionic bonding in metals at the beginning of her course. She thought there would be some sort of bonding in iron: as figure 1 "looks like lots and lots of iron atoms", and "they're all stuck together, so there must be something holding it together". Paminder reluctantly suggested that this was ionic bonding,

> "it could be covalent or ionic. Ionic, I think, because you know it is a two-plus, and two-plus that indicates that it is not covalent, it's ionic".

There was no indication in the figure that iron was 'two-plus', but Paminder recalled this association, and for her this was consistent with ionic bonding.

It was reported above that at the start of her course Jagdish did not think there was any bonding in metals, such as in figure 1. However, she later decided that there would have to be *some* bonding, and that "metals don't have covalent bonds", and so "metals have ionic bondings". However, when asked to elaborate Jagdish suggested that "the iron atoms lose electrons, and they form positive ions", and that the electrons would go to "non-metals" which were not on the diagram.

Although Jagdish recognised that there were only iron atoms present, she reported that the electrons "wouldn't go to another iron" but "to a non-metal". However for this to happen "there'd have to be something like heat or something too, for the reaction to happen". Jagdish was unable to explain the bonding without a non-metal for the iron to react with, but correctly recognised *something* had to hold the particles in the iron together,

> "But they do stick together, otherwise you wouldn't be able to see iron would you? If, if the atoms didn't stick, if the atoms weren't together, we wouldn't be able to see it."

6. metals have bonding similar to ionic bonding

Edward recognised a category of metallic bonding, describing the arrangement in figure 1 as

> "an example of metallic bonding, close packing. Basically how marbles would arrange themselves if you put them into a solid container"

However, he used ionic bonding as a referent for explaining the metallic bonding, which was,

"*similar to ionic bonding*, in the fact that you've got, positive and negatives…and the electrostatic… attraction between the two, because you've got the metal positive ions in the lattice, held together by their attraction for the pooled electrons."

7. metals have ionic and covalent bonding

In Debra's first interview she thought that the bond in a metal (figure 1) comprised of the atoms "sharing electrons, pair of electrons *and* there's free electrons, within the metal, that are free to move". The 'sharing electrons' component was covalent, and the "electrons that are free to move in the substance, and they're attracted to the positive", was a second type of bonding which was "like ionic". So Debra's conceptualisation of metallic bonding was in terms of the covalent *and* ionic categories.

The idea that metals had several types of bonding was also found in a response from one of the college students in a written test,

> "Metals are good conductors because they contain only a few co-valent bonds, mainly ionic and Van der Waals."

8. metallic bonding only occurs in alloys

In Umar's first interview he saw figure 1 as representing a "load of iron atoms" which might be bonded by metallic bonding: which only occurs in metals, and involves a 'sea of electrons' to hold it together. However, Umar was unable to provide any information about the sea of electrons, something that he found "a bit difficult to put it into words". He suggested,

> "in metallic you've got positive ions and negative ions, and like the positive attracts negative ions…they're already charged ions, and they attract each other"

However, when asked to suggest an example of a metal (he chose tin) and explain his ideas, he withdrew this suggestion,

> "no it won't have any bonds in it, because it's just pure, ain't it? It will be just atoms, it won't be charged"

However, Umar did think that something "attracts atoms together to form *molecules*". Umar's conception of metallic molecules appeared to be related to an atom's covalency. That is, the number of atoms in a tin 'molecule' "depends [upon] how many electrons in the outer shell, how many bonds between each atom there are". So Umar did think there would be bonds in a *pure* metal, although these would not be metallic bonds.

Umar thought metallic bonds existed "between two metals". So, for example, in an alloy between chromium and iron "it would be the ions that are bonded together" and "chromium might be … negative, and iron be positive, so they'd attract each other". Near the end of his first year Umar described metallic bonding as "a bit like ionic I think, but it's only between metals".

So it seems that at the start of his course Umar *knew* of the term 'sea of electrons', but he seemed to have no strong mental model for what this might mean. When he was probed about his understanding of the metallic bond he offered a model based on ionic bonding (which he was able to apply in the context of two different metals, but not in a pure metal), and a molecular model using the idea of covalency. However, the interview seemed to encourage Umar to revisit his understanding of this topic: in a college examination, shortly after describing metallic bonding as being similar to ionic, he produced the following explanation, "Metals are good conductors of electricity and, when heated in a vacuum, will emit electrons. This can be explained by the delocalised [electrons] present in all metals. These act as *a sea of electrons* and attract positive metal ions together to form a lattice. The positive ions are prevented from repelling one another due to the shielding affect by *the sea of electrons*. …"

9. metals literally have a sea of electrons

The 'sea of electrons' metaphor for the metallic bond is a very common one in science teaching. In Umar's case (above) we see development from this being a *rote* definition, to becoming a *meaningful* part of a coherent mental model.

Umar was not alone in initially learning the 'sea of electrons' metaphor as an isolated expression, without fully appreciating the model. For example, figures 3-6 reproduce students' diagrams, with their own words, from college examinations taken a few months before the end of their course. These show that the 'sea' may be represented as a *vast excess* of electrons which would not be possible in a neutral metal structure:

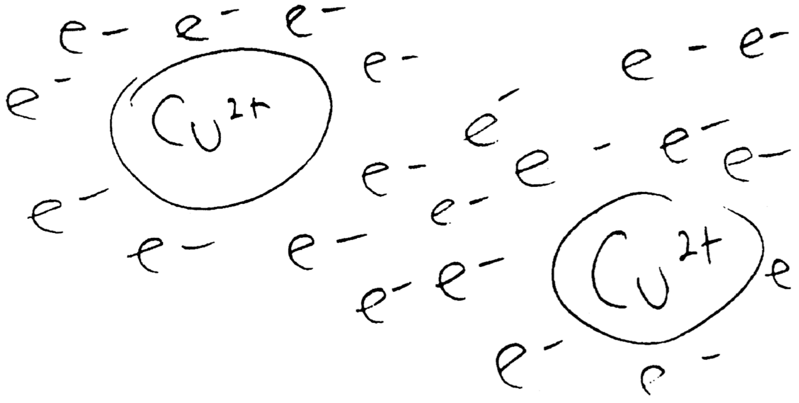

Figure 3. "Copper is held together by metallic bonding, where a central cation is surrounded by a sea of electrons."

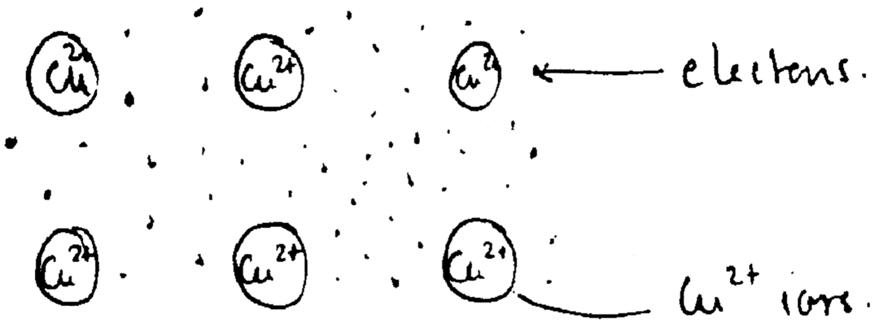

Figure 4. "Copper forms metallic bonds, i.e., its ions are surrounded by a sea of electrons."

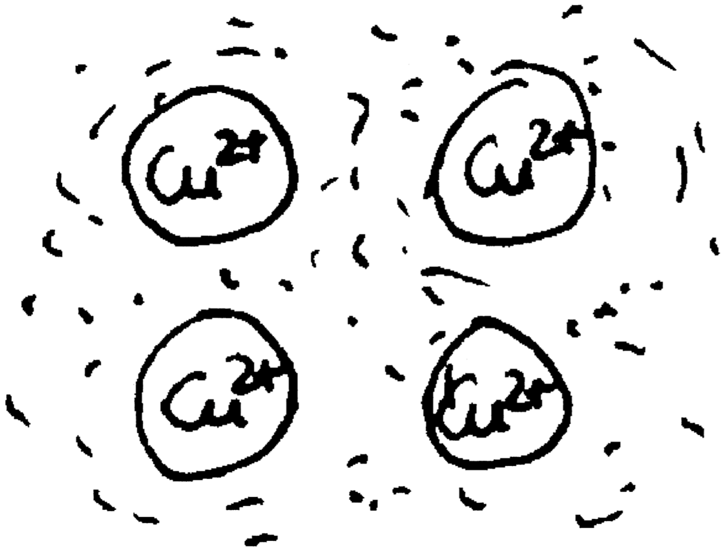

Figure 5. "Copper is a metal. It has a metallic structure consisting of metallic bonding i.e., positively charged ions in a 'sea' of electrons . . . ."

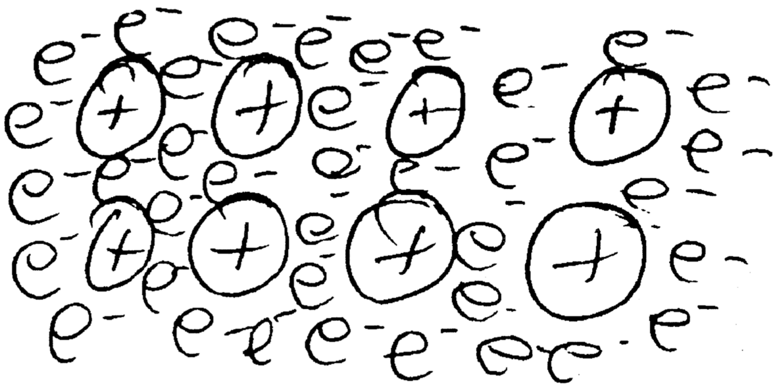

Figure 6. "Copper. This has mettalic [sic] bonding. In Mettalic [sic] bonding the atoms are held together in a 'sea' of electrons which acts like a glue."

In figure 6 we see that the function of the sea is to act 'like a glue', and a comment from another of the students may help to explain why the students assumed such an imbalance between electrons and cations,

> "Copper is a typical transition metal & shows metallic bonding with the cations (Cu^{2+}) sitting in a sea of anions (electrons). The electrons act like glue & there [sic] *great number* means that there is very strong bonding."

The 'sea' metaphor also seems to bring in related associations. Noor describe the electrons as swimming,

> "Metallic bonding is like a special kind of electrostatic bonding [where] the valence electrons in an atom *swim* free in the lattice of an metal, the positive atoms and the negative *swimming* delocalized electrons attract one another…"

Tajinder referred to electrons floating,

> "electrons like that *floating* around…*floating* about the sea of electrons, … they're *floating* around the outer electrons…they'd be electrons like *floating* about…"

Other students (in examinations, and concepts maps) referred to

> "*islands* of Cu^{2+} ions";
>
> "a positive charge being like an *island* surrounded by electrons";
>
> "a 'sea of electrons' *drift* about in metallic bonds"
>
> "metal ions are *suspended* in a 'sea' of dissociated 'free' electrons"
>
> "ions are *floating* in a sea of delocalised electrons."

10. metals have electrons delocalised to give full outer shells

Umar was also able to apply the explanatory principle that atoms seek full shells to metallic structures. He thought that iron atoms would spontaneously form a metallic lattice, but this was not due to electrostatic forces, but rather because,

> "in the lattice each ion is a positive ion so again…loses an electron to form a positive ion, so *to get a noble gas configuration*."

This utterance came near the end of his course: that is after Umar had been taught about models of metallic bonding involving electrostatic forces, and the overlap of valence shell atomic orbitals giving rise to an extensive system of molecular orbitals. Similarly, the following definition is from a revision exercise undertaken by a student at the end of the first year of the A level course,

> "metallic - formed by the one, two or three valent shell electrons being donated to lattice *so a noble gas configuration is achieved*. The electrons hold the atoms together."

Tajinder also sometimes conceptualised the metallic bond in terms of the full shells explanatory principle,

> "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 so it's quite high energy, so it wants [sic] 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"

At the end of her course Annie was thinking about the bonding in the metal in terms of the atoms "getting *a full outer shell*, but then they're sort of losing it, but then like the next one along will be receiving *a full outer shell*",

> "you've got delocalised electrons going round, the metallic atoms, in a sort of like a sea. So they're, they're all sort of freely flowing around…[as] metals haven't got full outer shells, then by electrons moving around, they're getting a full outer shell, but then they're sort of losing it, but then like the next one along will be receiving a full outer shell. So, *you've also got charges*, that are forces from the nucleus pulling, just attracting…electrons from outside in. But mainly due to, like delocalised electrons they can move about, so, then you've got forces keeping it all together"

In this extract Annie explains metallic bonding in terms of full outer shells, but then goes on to explain how there are '*also*' charges, and so forces 'keeping it all together'.

11. metals have a metaphorical 'sea of electrons'

Annie's apparent dual model of metallic bonding was reflected in the comments written by another student in a revision exercise at the end of the first year of advanced level study. In this case the student appreciates the electrostatic attractions between cations and electrons, but seems to consider the 'sea of electrons' as a separate feature:

> "Metallic bonding is only occrent [sic, only occurs] in metals and is the attraction between the positive charge of the metal ions and the negative charge of the electrons. It *also* has a sea of electrons which flow around the structure."

In Tajinder's first interview, he knew there was a category of bond called 'metallic', but seemed uncertain of the detail of this type of bonding, beyond the presence of free electrons,

> "Metallic bonding…I'm not sure what it is, but it's all like this [figure 1] but there's lots of like electrons, around, there's just free electrons roaming around, so that's why electric current can pass."

He reiterated that the metallic bond was,

> "where there's…lots of nuclei, of a certain kind, like say for instance iron, and there's electrons, which are free to move within a certain area, and this is metallic bonding".

Later in the year Tajinder made the comments (reported above) about how the atoms in lithium metal would be constantly giving away or passing around the electron. This was an attempt to explain metallic bonding in terms of atoms attaining full outer shells. However, he was *also* at this point able to discuss how the structure ("an arrangement, like nuclei, and there's a sea of electrons around them") also gave rise to,

> "the force of attraction-repulsion, attraction between the lithium nuclei and the surrounding electrons of other lithium nuclei…[and] the repulsion of the lithium nuclei and another lithium nuclei".

Tajinder continued to use the 'sea of electrons' metaphor, with electrons "*floating* around": describing the metallic bonding in lithium in terms of "a lot of lithium nuclei surrounded by a *sea* of electrons which are which are free to move around the outer shell of each lithium atom". Yet, unlike some students who seemed to feel that such a description was a sufficient explanation, he had managed to integrate this notion with ideas about the electrical interactions in the structure.

By the end of the first year of his course Tajinder was able to provide a relatively detailed and sophisticated explanation of metallic bonding,

> "metallic bonding takes place in metals, and this is where, say, you have sodium. Now sodium doesn't exist by itself [as] an atom 'cause it's not stable, and it's quite

> reactive. So it forms with other sodium atoms to form a type of solid. And this solid is where there's positive ions in the solid and the electron on outermost shell is like delocalised and it's free to move around the area, and only electrons in the outermost shell can take part in metallic bonding and what holds it together is *the attraction* between the electrons and the positive ions, between one another, that's what holds it together. If you have magnesium which has two outer electrons, then two electrons can become involved in the sea, in the solid, and they're called the sea of electrons, going moving around the positive ions, and that's why you can pass electric current through metal because the electrons are free to move through a metal so that's how they can pass on electric current."

So, Tajinder's vague knowledge of 'free' electrons at the start of his course evolved into a type of bonding involving electrostatic interactions, but described in terms of electrons 'floating' in a 'sea'.

Discussion

The data presented in this paper come from the very limited context of a particular level of study in a single college in one educational system. It would clearly be inappropriate to generalise from this particular small sample to make broad claims about learners' mental models for metallic bonding. However, in view of the limited discussion of this topic in the literature, this study does provide some point of reference for others interested in investigating this concept area, and there is some consistency with previously reported work (Fleming, 1994; de Posada, 1997; Harrison & Treagust, 2000; Coll & Taylor, 2001, 2002).

However, this paper's main purpose is to provide an in-depth look at the evolving mental models of this particular group of students, in order to explore how they made sense of what was in effect a new category (metallic) within a domain familiar from prior learning (chemical bonding).

This study is located within the developing tradition of exploring the process of science learning which requires detailed investigation of the learning of individuals (Harrison and Treagust, 2000; Johnson, 1998; Petri & Niedderer, 1998, Scott, 1992, Taber, 1995, 2000d, 2001b). Although it is *not* possible to know if the *specific* findings reported above are typical of the mental models for metallic bonding to be found in other populations, it *is* possible to suggest that this case study provides strong evidence of the way prior learning can channel the development of learners' ideas.

At the start of their college course these students tended to conceptualise metallic bonding in one of a limited number of ways:

- there is no bonding (or no proper chemical bonding) in metals

- the bonding is ionic and/or covalent

- there is a sea of electrons

By the end of their two year course students had made varying amounts of progress in moving towards the curriculum target: an appreciation that a metal could be considered to be held together by a distinct form of bonding, metallic bonding, which involves electrical interactions between a lattice of cations and delocalised electrons. Students' ideas developed, but not always as quickly or as far as would be desired by the teacher.

It is not intended to mock the various mental models that these students held on their way to developing a more scientific understanding. Rather the aim of this paper is to critique *the conceptual resources available to students* at the start of their college course. Prior learning can provide the bed-rock on which new ideas can be anchored: but whereas *appropriate* conceptions can act as bridges (or stepping stones) to a new understanding, *inappropriate* conceptions can act as barriers (Taber, 2002a).

It is clear that some students did not initially realise that a pure metal would need bonding to hold together. This may seem an odd finding to teachers, but we need to remember that the molecular models so familiar to us are both novel and abstract to our students (Taber, 2001c, 2002a). For some students the notion of the chemical bond was much more strongly associated with 'achieving a full shell' than maintaining a structure. The nature of many representations of metallic structure, as close packed spheres, do not make bonding explicit. Figure 1, whilst typical of many textbook illustrations, does not offer students any cues to invoke bonding (whereas familiar representations of covalent or ionic bonding show the bonding by lines, shared electron pairs or charges).

Some students associated bonding primarily with compounds, and so thought that elements would not need to be bonded - something that is consistent with the common 'assumption of initial atomicity' that students often make when thinking about chemical reactions between elements (Taber, 1998, 2002a). Certainly the students discussed here strongly dichotomised bonding according to a simple typology (*electron sharing* between non-metals, and *electron transfer* from a metal to a non-metal), that did not provide scope for bonds *within* metals: (Taber 1998).

This also explains why it was found that even when students did understand that *something* was needed to maintain a solid structure, they were reluctant to consider this as a form of chemical bonding. Chemical bonding was understood to be about atoms obtaining full shells by sharing or transferring electrons, which did not seem to apply in the case of metals. Like hydrogen bonding, van der Waals' forces, solvent-solute interactions and even most of the interactions between ions in ionic lattices (those where electron transfer is judged not to have taken place between the ions concerned), the metallic bond was not considered to be a proper bond (Taber, 1998). As Annie explained "you haven't got like actual bonds in metallic bonding [as] you're not getting electrons completely transferred or shared".

For those students who concluded that the structural integrity of metals *must* imply a form of bonding, there was a reluctance to move outside of the covalent-ionic dichotomy. Some students felt that the best fit was to the covalent category. Mike and Kabul tried to make sense of the bonding by extending the notions of covalency and molecules to the metallic case. If a metal has two outer electrons then this may be taken to imply something about the number of bonds it will form rather than the charge on the lattice cations.

This provides an interesting parallel with the way students have been found to develop an inappropriate notion of electrovalency in the ionic case, assuming that the number of electrons to be 'donated' or 'accepted' in ionic bonding determines the number of ionic bonds formed and not just the ionic charges (Taber, 1994, 1997b). It has been suggested that where learners are first introduced to chemical bonding in the context of covalent bonding in discrete molecules, students interpret subsequent teaching about the ionic bond from within their freshly acquired 'molecular schema' (i.e., ionic bonding is seen as involving small groups of atoms bonded to meet valency requirements - Taber, 2001c), and in the present study we see students interpreting metallic bonding in a similar way.

Other students based their model of metallic bonding on the ionic case, often taking their cue from the presence of charges in the structure (something usually made explicit in representations of the ionic case and so associated with ionic bonding): so Paminder referred to the "two-plus that indicates that it is not covalent, it's ionic".

However applying the ionic schema to the metallic examples was itself problematic, especially as students tended to equate ionic bonding with electron transfer. So when Jagdish tried to explain metallic structure in terms of ionic bonding she was channelled into thinking about metals *and* non-metals. Her train of thought was:

1. metals are held together, so must be bonded;

2. metals do not have covalent bonds;
3. therefore they must have ionic bonds;
4. in ionic bonding the metals donate electrons to non-metals

In this way she moved away from the original focus, i.e. bonding in a pure metal, and was unable to suggest an acceptable solution. Of course the flaw in her logic was the tacit assumption in step 3 that there were only two possible types of chemical bond.

Umar was able to take this line of argument further than Jagdish, by considering that *in an alloy* one metal might act as the electron acceptor (in effect considering electronegativity differences between different metals), but he still could not apply the approach to a pure metal.

Edward was able to transcend this logical enigma by conjecturing that the bonding in a metal was *similar to* ionic bonding rather than *being* ionic bonding. For Edward the metal case was "similar to ionic bonding, in the fact that you've got, positive and negatives".

Here we see that the same conceptions which can act as a block to further learning can also act as the resources for developing new understandings. Some students took this approach further and drew on both the covalent and ionic models to develop an image of metallic bonding. Debra's conceptualisation that metallic bonding included shared electrons as well as electrons that are free to move is actually quite a good way of thinking about bonding in d-block metals (iron, chromium, cobalt, manganese, nickel, titanium, vanadium, etc.) where the outer shell electrons (e.g. in the N shell in period 4 elements) may be considered delocalised, but the strength of bonding also depends upon interactions between 3d-orbital electrons in the M shell which are *not* delocalised over the structure. The electronic structures are actually more complex than this (Pauling, 1960) but the principle that the bonding has significant covalent character would seem sound.

Some students were able to extend their dichotomy of bond types within the overarching octet framework. For these students the donation of electrons to the lattice was the way in which atoms obtained full outer shells (although in some versions this was a transient process, with electrons passed around and atoms considered to be taking turns in having the full shell).

Those students who were aware of a separate category of metallic bond at the start of their course tended to define it in terms of the presence of a sea of electrons. However, although they might connect the free electrons with the metal's conductivity, they were initially unable to explain why this bonded the metal together. Students seemed to accept the 'sea' metaphor uncritically, and to develop images of cations and/or electrons floating, swimming, etc. in the sea without thinking through the consequences of such a model. In particular the 'sea' notion was taken to imply a vast excess of electrons which would have removed any structural integrity from the metal.

As with prior learning about ionic and covalent bonding ('bonding is covalent *or* ionic (= 'bonding is electron-sharing *or* electron-transfer'), the presence of the notion that 'metallic bonding = sea of electrons' was able to act either as an impediment to further learning - by acting as a 'pseudo-explanation' (Taber & Watts, 2000) standing the place of any deeper understanding - *or* as an intermediate conception on a learning pathway.

Research suggests that students differ in what they expect from a scientific explanation (Gilbert, Taber & Watts, 2001) and that some students do not push the cycle of 'why' questions through many stages before accepting that they have reached the 'that's just the way it is' stage (Watt & Taber, 1996). Some students seem content with knowing that 'metals have metallic bonding, which means they have a sea of electrons' even when this can not be considered to give any depth of explanation.

Other students seem more ready to *develop* the 'sea' metaphor in relation to ideas about orbital overlap or electrical forces, to provide both a more meaningful framework for interpreting the metallic bond, and a model that is more coherent with developing understanding about other types of bonding (Taber 2001b).

Conclusion - consequences for curriculum planning and teaching

The constructivist perspective on teaching science is based upon the assumptions that (i) information is interpreted through, and (ii) new learning highly dependent upon, existing conceptual frameworks. The present study exemplifies these principles. Student learning about metallic bonding during a two year college course was found to be strongly channelled by prior learning. In particular, students' existing conceptions for bonding were found to be tied to the 'octet framework': bonding occurred when atoms either shared or transferred electrons to get full outer shells.

Most students started the course without a substantial mental model of metallic bonding. Those who were actually familiar with the notion either just knew the term, or had learnt the phrase 'sea of electrons'.

During their college course these students were expected to develop *an understanding* of metallic bonding. They would be taught about electronic orbitals and how molecular orbitals may be formed which - in the case of metals - could be extensive.

However, at the start of their course, these ideas were not available to the students. Most of those interviewed had clearly never thought before about why metals have structural integrity. When asked if there was bonding in figure 1 these students naturally accessed their existing knowledge about chemical bonding: i.e. about covalent and ionic bonds. Bonding in metals was either fitted into this dichotomy, or tended to be discounted as *something other than* proper chemical bonding.

One aspect of the 'octet framework' is the common 'assumption of initial atomicity', i.e. that when students are asked to think about a chemical system (such as a reaction) at the molecular level they tend to conceptualise a starting point in terms of separate atoms (which allows students to 'explain' the reaction in terms of the atoms acquiring full shells).

Students often tend to think that the 'natural' state for elements is as atoms (cf. Watts & Taber, 1996), so that solid carbon, for example, may be visualised as discrete atoms (Taber, 2002a). This tendency is strong enough for some students to assume that a pure metal does not need to be bonded (as it is an element). This in turn means that any questions about bonding in metals seem to trigger a 'bonding *with what*?' response that channels thinking them away from the intended focus.

Some students had learnt while in school that there was a category of bond called 'metallic'. For these students the term 'sea of electrons' seemed to have been learnt by rote, without any meaning being explored. Humans naturally try to make sense of our experiences, and this study suggests that students will attempt to develop a mental model from such a minimal scrap of information. Slogans can be very effective, and the 'sea' metaphor was developed both *visually* (with mental images including enough electrons to justify the sea label - see figures 3-6) and *verbally* by including water-associated terms such as floating, swimming, etc.

This does not indicate that the 'sea of electrons' comparison should not be taught, but rather that, like all metaphors and analogies used in teaching, it needs to be explored in the context of prior learning when first presented, so that the learner makes the intended sense of it (Taber, 2001d, 2002a) and is not left to guess what the relevance is. It would seem good practice when sailing on the real sea to use charts to find out where your boat is located before dropping anchor. Similarly, it makes sense for a teacher to check the 'cartography' of a learner's cognition (Wandersee, 1990) before dropping an Ausubelian anchor such as the 'sea of electrons' metaphor.

The creativity and imagination of students is sometimes quite astounding. As reactions do not occur because atoms need to obtain full shells (as in most chemical reactions the products *and reactants* satisfy the octet rule), it may seem strange that so many learners develop this view. Yet introductory chemistry courses (e.g. 14-16 years) have little to say about the key question of why chemical reactions do happen, and learners commonly 'fill the explanatory vacuum' with the most likely suspect by adopting and extending the octet rule (often abetted, it must be acknowledged, by some very dubious text book presentations - see Taber 2002a).

The value of studies which explore learners' changes in thinking in depth (e.g. Taber, 1995, 2000d, 2001b) is to go further than just *identifying* alternative conceptions or preferred mental models, but rather to inform teachers about the learning process itself. Such studies shows us that given time and suitable instruction students can often manage to adapt and develop their mental models to bring them closer to the curriculum targets. However, this can be a slow process.

In the present study, a number of features of prior learning seemed to retard learning about a scientific model of the metallic structure:

- thinking of elements as being atomic in nature;
- thinking of bonding as being about obtaining full shells;
- thinking of bonding as being limited to two classes (covalent and ionic);
- having an undeveloped slogan for metallic bonding ('sea of electrons').

This study shows the importance of carefully planning the sequence and level of teaching a topic such as chemical bonding, and the potential consequences of oversimplified models (bonding is covalent *or* ionic), isolated teaching analogies (metals have a sea of electrons), and ignoring difficult questions (why do chemical reactions occur?)

Often school level courses first present the covalent bond, then the ionic, and treat metallic bonding as an after-thought, if at all. It has previously been suggested that some of the common alternative conceptions *about ionic bonding* result from inappropriate application of previously taught ideas about covalent bonding (i.e. valency and molecules), and the findings discussed here suggest that understanding *of metallic bonding* is also highly dependent upon students' previously acquired models of covalent *and* ionic bonding.

The present study draws evidence from a single context, and more research in other educational systems would be welcome. However, the research reported here suggests that school science teaching may not be providing learners with appropriate prior learning to help them develop the model of metallic bonding and structure required at college level. (According to the wider research project, the same conclusion applies to other topics met at this level: such as ionisation energies; polar bonding; hydrogen bonding; ionic reaction mechanisms, etc.) This would indicate that teachers and curriculum planners should consider making a number of changes to the teaching of this area of chemistry:

introduce a general notion of bonding, based on electrical interactions, before exploring specific bond types in detail;
emphasise bonding as the interactions which hold structures together (rather than being related to developing full shells);
emphasise that most elements are not atomic (and that reactants in chemical reactions do not tend to be atomic) and are therefore chemically bonded;
similarly, emphasise that chemical bonding is present in reactants as well as products (so that metallic bonding is not tied to the metal reacting with another element);
consider changing the order of teaching about bonding types (e.g. it has been suggested that complexity increases from metallic, to ionic, to giant covalent, to simple covalent structures, Taber 2001c) to avoid inappropriate specific aspects of one model being transferred to others;
take time when introducing the 'sea of electrons' notion to explore the metaphor so that so that learners can use it as the basis for a scientifically appropriate model.

Most of these points concern teaching the topic with a particular emphasis (i.e. in terms of charges and forces), and with care not to *over*-simplify (bonds are either covalent or ionic), nor to rely too heavily on metaphorical language (what atoms 'want', 'seas' of electrons), nor to leave an explanatory vacuum (no rationale for bonding or reactions occurring) into which other concepts (such as the octet rule) can expand beyond their valid range of application. These suggestions are unlikely to be seen as drastic, although teachers may find that the habitual nature of existing teaching practice makes them difficult to adopt.

Perhaps the most drastic recommendation is to change the order of presentation of bonding types (Taber, 2001c - see table 1). As basic chemistry curriculum requirements often only specify that students should be able to discuss covalent and ionic bonding then it is common practice to concentrate on these types of bond. This is perhaps based on a view that these forms of bonding are the most important, although substances with metallic and simple molecular structures are very common.

Yet from a logical point of view it could be argued that the simplest form of bonding to understand (in basic terms) is metallic bonding. A metal can be modelled as atoms of a single type that overlap their outermost shells to give a lattice of cations (atomic cores) surrounded by a balancing number of bonding electrons. Of course such a description of metallic bonding remains limited without an appreciation of orbital interactions, but students should be able to appreciate the idea that a positive atomic core will attract and be attracted by electrons from surrounding atoms (as well as its own), and so there is a physical reason for atoms to come together. (Eventually similar charges are too close for any further overlap to occur). At this point the valency electrons can be considered to be able to move between the overlapping outer shells leading to the conductivity of metals.

This is a simplified and partial model: but it is one which has a rationale that has a physical basis (i.e. the attraction between opposite charges, rather than atoms trying to get full shells), and which is a suitable basis for developing more sophisticated models in due course.

Once metallic bonding is understood in these, electrostatic, terms, then students are in a better position to appreciate ionic bonding as the force between positive cations and negative anions

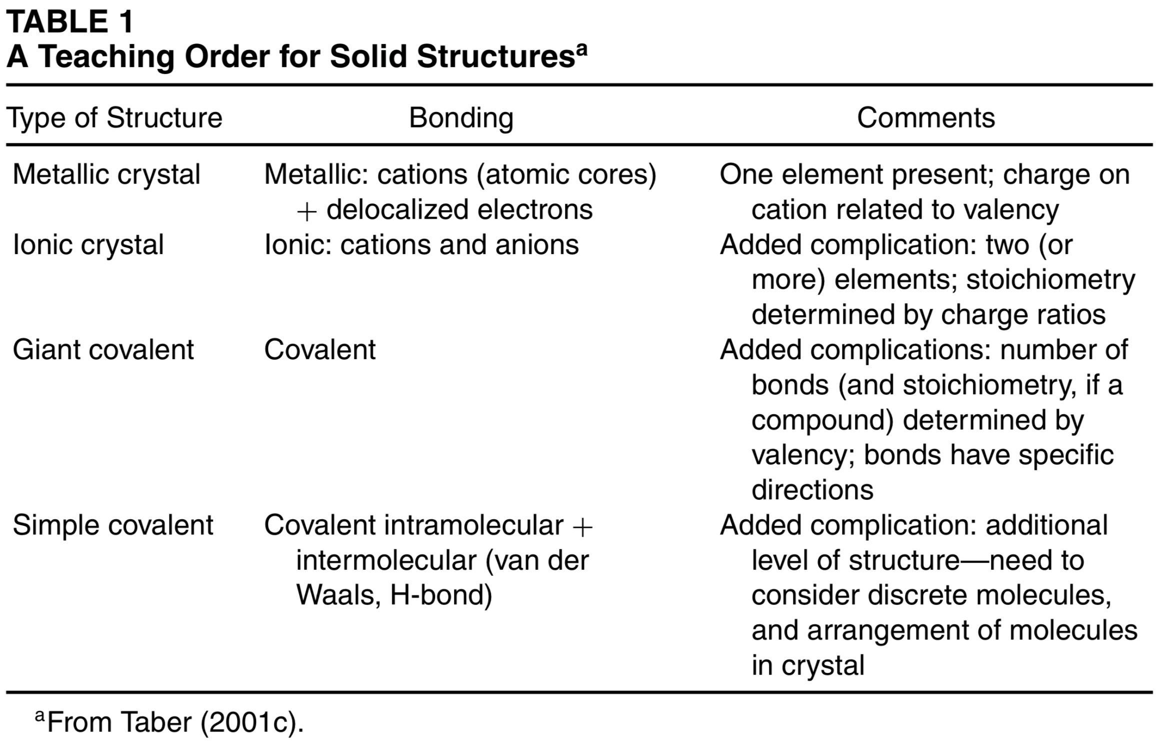

TABLE 1
A Teaching Order for Solid Structures[a]

Type of Structure	Bonding	Comments
Metallic crystal	Metallic: cations (atomic cores) + delocalized electrons	One element present; charge on cation related to valency
Ionic crystal	Ionic: cations and anions	Added complication: two (or more) elements; stoichiometry determined by charge ratios
Giant covalent	Covalent	Added complications: number of bonds (and stoichiometry, if a compound) determined by valency; bonds have specific directions
Simple covalent	Covalent intramolecular + intermolecular (van der Waals, H-bond)	Added complication: additional level of structure—need to consider discrete molecules, and arrangement of molecules in crystal

[a] From Taber (2001c).

holding them in a lattice arrangement (rather than seeing ionic bonding as electron transfer to form ion pairs). Only after learning about these two forms of bonding should students be introduced to covalent bonding, with its complications of valency and bond directions.

Table 1: a teaching order for solid structures (from Taber 2001c)

type of structure	bonding	comments:
1. metallic crystal	metallic: cations (atomic cores) + delocalised electrons	one element present; charge on cation related to valency
2. ionic crystal	ionic: cations and anions	added complication: two (or more) elements; stoichiometry determined by charge ratios
3. giant covalent	covalent	added complications: number of bonds (and stoichiometry, if a compound) determined by valency; bonds have specific directions
4. simple covalent	covalent intramolecular, plus intermolecular (van der Waals, H-bond)	added complication: additional level of structure - need to consider discrete molecules, and arrangement of molecules in crystal.

One further point that should be made is that it is important *not only* that students are introduced to models that are simplifications suitable for being extended and developed, but also that they are made aware that these are models. Research suggests that students often tend to consider that scientific theories as facts, and to think of scientific models as scaled-up or scaled-down copies of phenomena (Driver et al., 1996; Grosslight et al., 1991). For a teaching model to be a sound foundation for developing more sophisticated conceptions it is important that it *is* as consistent as possible with the advanced models to be met later: but *also* that it is perceived by the learner to be - like scientific knowledge itself - a tentative and interim understanding. A student who learns in school that bonds ARE either covalent or ionic is understandably resistant to learning about intermediate or other forms of bond; and similarly a student who learns that THE way to think of metallic bonding is in terms of atoms overlapping their outer shells may find it difficult to later consider an analysis in terms of conduction bands.

What is suggested here, then, to improve students' understanding of metallic bonding, is a strategy with three strands, each based on the consideration of research evidence:

a) a strong emphasis on *forces* as the basis of chemical bonding (to avoid students developing explanations based on atoms trying to fill their shells);

b) a re-ordering of the teaching sequence for introducing bonding, starting with the simplest type of bond (to support the development of more scientifically based understandings, and to avoid students transferring features of covalent bonding to the ionic and metallic cases);
c) an explicit teaching of curriculum models as useful tools for thinking about science, which offer limited and partial ways of understanding phenomena (both to give a greater appreciation of science itself, and to prepare students for the need to modify and develop their understanding).

The evidence from the students discussed in this paper suggests that these shifts in the way bonding ideas are presented could help students develop acceptable (i.e. matching to curriculum targets) models of metallic bonding quicker. These suggestions need to be explored in practice to see if they can indeed facilitate student learning of the models presented in the science curriculum. However, whatever planning decisions are made at national, institutional or classroom level, they are only likely to be effective where they acknowledge the priority of the learner's prior learning,

> "the teacher should keep in mind that his first obligation is to ensure that the requisite *initial* learning has taken place"
>
> (Ausubel & Robinson, 1971, p.157).

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