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Chemistry Learners' Preferred Mental Models for Chemical Bonding

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ABSTRACT

Preferred mental models of 30 learners from three educational levels, senior secondary, undergraduate, and graduate (master of science and PhD) were probed using a three-step interview protocol. In the first step the participants were shown common substances such as table salt and asked to explain the bonding. Next they were shown events depicting physical or chemical properties (for example malleability and conductivity) and asked to use their mental models to explain the event. Finally, they were shown depictions of mental models drawn from curriculum material and asked for their preference. Data also were collected from curriculum material and interviews of faculty. These latter data resulted in the identification of three target systems for chemical bonding (namely, metallic, ionic, and covalent), and eight target models (molecular orbital theory, sea-of-electrons, etc.) which were negotiated and became socially-situated consensus teaching models, used to interpret interview data. The findings suggest learners across all academic levels prefer simple, realistic-looking mental models, and varied to the extent to which they were able to use them to explain common physical and chemical properties of substances.

Keywords: Mental Models; Chemical Bonding; Chemistry; Alternative Conceptions

INTRODUCTION

The latter part of last century witnessed a huge research effort into learners understanding of scientific concepts. Much of this research has been concerned with perceptions of learners' inabilities to understand scientific concepts or to develop conceptual understanding about mental models that are in accord with scientific or teaching models (Garnett et al., 1995; Pfundt & Duit, 1994, 1997, 2000). Theory-making and practice of chemistry and science is dominated by the use of mental models. This it is argued by many authors occurs since when scientists seek to understand macroscopic properties they inevitably need to consider what is happening at the microscopic level (see for example Oversby, 2000). Because we cannot see what happens at the microscopic level we need to develop mental images or mental models of what matter and its changes might be like at this level. This macroscopic-microscopic link in chemistry can be traced to the development of the atomic theory. Scientists' current theory of the nature of matter is intrinsically linked to Dalton's notion of the atom and the atomic nature of matter.

Atomic theory, although tremendously successful, is nonetheless a theory, a mental model of how scientists view the makeup of material world that surrounds us. Many other theories and mental models in science and chemistry build upon atomic theory and this has important implications for the teaching of abstract mental models as is discussed below.

Examination of chemistry content at different educational levels shows how deeply embedded mental models are in chemistry content, and consequently in chemistry teaching and learning (Coll, 2005; Coll et al., 2005; Eduran & Duschl 2004; Justi & Gilbert, 2005). Harrison and Treagust (1996) propose a typology of mental models which includes chemical formulae, mathematical models, analogy, physical artefacts, and diagrams such as maps. A chemistry learner will of course need to learn things other than specific chemistry models to 'understand' chemistry to the satisfaction of his/her teachers or chemistry professors (e.g., chemical process and reactions, conventions for naming compounds, etc.), but every feature of chemistry content and learning includes the use of at least one mental model (according to Harrison & Treagust's 1996 typology). As a consequence, the learning of chemistry requires learners to learn about a variety of mental models, and learning about mental models dominates the learning process for this discipline (Hammond et al., 1971; Harrison & Treagust, 1998).

1) The Nature of Mental Models

Mental models are one form of mental images, and as such represent personal mental constructions (Johnson-Laird, 1983). These personal constructions are subject to a number of influences. Writers such as Piaget and Inhelder (1974) and Ausubel (1968) have stressed that mental construction depends strongly on what mental images individuals possess at the time they are attempting to learn new concepts. Educational psychologists have built on these notions about learning and knowledge acquisition, usually called constructivism, and there is now increasing recognition of the importance of other mitigating factors in mental construction, especially social factors (see Tobin, 1993, and references therein). This has resulted in a shift away from the rather simplistic view of personal mental construction, resulting in variants of constructivism in which authors use qualifying terms to modify or build upon the notion of personal constructivism (Good et al., 1993). For example, social-constructivists see social interaction (with say peers or teachers) as an important feature of mental construction; similarly, contextual constructivists see the educational context in which learning occurs as crucial.

The literature then suggests that mental models represent personal mental constructions, although the process of construction may be mediated by a variety of factors. The personal nature of mental models means that they are intrinsically difficult to investigate. Gilbert et al. (2000) point out that what researchers encounter or uncover during inquiry are in fact participants' *expressed* mental models; in other words, how they describe their mental models to education researchers. In some instances this results in methodological complications and, for example, Johnson and Gott (1996) talk about difficulties involved in developing a reliable understanding of participants' mental images via the discourse that occurs during interviews. Individuals may hold a particular mental model, but find it difficult to express or articulate this model in manner that is clear and meaningful to a researcher (see also Norman, 1983). Furthermore, an individual's mental model may not be the 'neat' or consistent artefact that appears in textbooks or that researchers construct during inquiry. Glynn and Duit (1995) comment that individual mental models are 'sloppy' and 'inconsistent', irrespective of any difficulties associated with verbalization expressing of personal mental models. Hence, comparison of individuals' mental models is commonly associated with inquiry that works from a deficit model in which learners' mental models are compared with scientific or 'correct' teaching mental models that appear in textbooks or lecture notes.

2) Scientists' Mental Models

One of the key findings from the science education literature is that scientists and expert modellers see and use mental models in very different ways to novices or learners - and indeed many teachers (Coll, 2005). Teachers tend to use models to aid understanding, and, for example, draw upon analogy to guide learners towards a 'better' understanding of the 'correct' model (Dagher 1995a, 1995b; Gilbert & Boulter, 1998; Justi & Gilbert, 2005; Weller, 1970).

Scientists understand that a model by definition has limitations (Maksic, 1990). That is, models share only some attributes with the target (what is to be modelled). As a consequence, as Zumdahl and Zumdahl (2002) point out, if a model did not possess limitations (that is, differ from the target in some way) it would in fact become the target or artefact (or process) that is being modelled. This does not mean that scientists discard models that possess limitations, indeed they continue to use models - even models that possess severe limitations; they are pragmatic about model use and clearly understand the limitations of the models they use. A simple example germane to this inquiry is the so-called ligand field theory (also often called crystal field theory, see Coll & Treagust, 2002). In this model the bonding between atoms or groups of atoms surrounding a metal centre is proposed to arise from pure electrostatic interaction between an electron deficient centre (the metal) and attached electron rich groups (usually called ligands). This electrostatic interaction results in the formation of a 'field' that attracts the ligands to the metal; even a cursory examination of this model shows clearly how simplistic and crude a model it is. The model also possesses many well-established limitations (e.g., it fails miserably to explain the spectrochemical series), but the crystal field theory is still in common use even in research chemistry (see, e.g., Smith, 1994). Why do scientists use crystal field theory in their research if it possesses such severe limitations? Simply because it works well in certain *well-defined* circumstances; and with characteristic pragmatism chemists use this rather crude model as a tool that they find helpful to understand aspects of chemistry (see also Zumdahl & Zumdahl 2000 for an excellent illustration of a similar example based on the Aufbau principle of electron configuration, and Coll & Treagust, 2003b, for further discussion of this). Scientists thus see models in a functional, utilitarian capacity, and recognise that a model is intended to serve the user (Borges & Gilbert, 1999).

Scientists are able to visualise mental images of abstract things rather than physical entities. So whilst learners and novices are able to mentally picture physical objects or artefacts, scientists are able to conduct thought experiments and use mental models to conduct mental 'experiments' for the purpose of prediction. Another key difference between scientists and novices use of mental models is the tendency for scientists to use multiple models (Coll, 2005; Coll et al., 2005, Eduran & Duschl 2004, Williams et al., 1983). In doing so, the scientist is commonly constructing a mental model based on another mental model. To illustrate, scientists' mental models of chemical bonding are themselves based on another abstract mental model - the atomic theory which posits that matter is made up of small, microscopic particles of a specific nature and form.

Scientists thus use mental models for a variety of purposes. They use them to understand macroscopic phenomena as described above, but they also use mental models to generate new hypotheses (Justi & Gilbert, 2005; Holyoak & Thagard, 1996; Wong, 1993a, 1993b) and may go on to modify or use their mental models to evaluate and expose the limitations of their own scientific inquiry (Cosgrove, 1995).

3) Teaching Learners about Chemistry's Mental Models

The teaching of and use mental models in the classroom is reported to be idiosyncratic and quite commonly involves the use of analogy. Dagher (1995a, 1995b), for example, reports that teachers draw upon analogy when they feel their explanations have not been understood by learners. Analogy use has been reported to aid learner understanding of variety of mental models like kinetic theory to explain dissolution (Stavey, 1991, 1995; Taylor & Coll, 1997). However, research shows that even with the use of analogy confusion between the model and modelled abounds, and it is common for learners to confuse the model with reality (see, e.g., Lawson et al., 1993).

There are numerous reports in the literature alluding to problems encountered in the teaching of mental models and a number of themes emerge. As pointed out above, learners seldom see mental models as mental constructions. This it seems comes about because learners frequently confuse mental models with physical models seeing models as copies of reality, in effect scale models of some microscopic item or artefact. This results in a number of alternative conceptions and here I describe some for the topic of chemical bonding and related topics.

Harrison and Treagust (1996) found that secondary school learners thought of atoms as small spheres or balls (attributed to images from tunnelling electron microscopy), and Butts and Smith (1987) report confusion between ball-and-stick models and mental models. Common themes about learners' alternative conceptions for chemical bonding to emerge from the literature include confusion of inter- and intramolecular bonding (Coll & Taylor, 2001; Taber, 1998), confusion over polar covalent bonding and ionic bonding (Coll & Treagust, 2002, 2003b; Taber, 1995a, 1998), seeing metallic bonding as weak or inferior (Coll & Treagust, 2003a; De Posada, 1997; Taber, 1998), that the formation of ionic bonds occurs as a result of electron transfer (Oversby, 2000; Taber 1995b, 1995c, 1997; Taber & Coll, 2002) and seeing continuous lattices as molecular in nature (Birk & Kurtz, 1999; Coll & Treagust, 2002; De Posada, 1997).

The literature thus points to significant difficulties in learning and teaching of mental models in both science and chemistry. Studies of learners' mental models are dominated by a few conceptual themes, namely, atomic theory (Harrison & Treagust, 1996) and kinetic theory (Taylor & Lucas, 1997), with few studies on chemical bonding (see, however, Nicholl, 2001; Taber & Coll, 2002). This is a remarkable observation given that an understanding of chemical bonding theory is crucial to the understanding of most chemistry (reaction chemistry, stereochemistry and industrial chemistry, to name a few). A further limitation of the literature is that research is dominated by studies at the school level (especially the secondary school level) with most tertiary level studies confined to freshman or entrant level tertiary learners (see Laws, 1996). This work sought to contribute to the literature by conducting an inquiry into senior secondary, undergraduate and graduate learners' preferred mental models for chemical bonding.

4) Research Aims and Objectives

The focus in this inquiry was on the nature of chemistry's mental models for chemical bonding and the mental models as seen by teachers and faculty, what mental models learners possess for a variety of chemical substances, how the learners understood their own models, and finally how learners were able to use their mental models to explain physical or chemical phenomena. As learners progress through an academic career they encounter increasingly complex and abstract mental models for chemical bonding. The researcher was interested to see if themes or patterns of model understanding and use emerged with this increased exposure and learners' educational experiences. There was no systematic attempt to discern learners' *alternative conceptions* for chemical bonding. During discourse some alternative conceptions for learners' mental models were identified and these are described in detail elsewhere (Coll & Taylor, 2001).

5) Theoretical Underpinnings and Methodological Approach

This inquiry has been conducted within an interpretive paradigm with a social-constructivist view of learning (Tobin, 1993). The methodology derived from this framework comprised an approach in which individual constructions were elicited by interactive dialogue between the researchers and the participants (Good et al., 1993). This dialogue recognized the social aspects of knowledge acquisition and personal beliefs (Lave, 1991) and thus was conducted on neutral ground in order to reduce the influence of investigator bias (Johnson & Gott, 1996). In practical terms this consisted of the interviewer constantly working to ensure undistorted communication took place: words that hold an 'established' scientific or science teaching meaning were only ascribed the meaning imparted to them in the conversation of the interviews. For example, no implicit assumption was made that any of the terms that arose during interviews were seen in the same way (e.g., 'cloud' and 'sharing' in relation to 'electron') by learners and the researchers.

The researcher also drew upon recent writings that emphasize the situatedness of learning and the importance of the social context in which the learning occurs. It is suggested above that scientists see mental models in particular ways and use them for particular purposes. It is common then to talk about *scientific models* and many authors refer to scientific models, ostensibly seeing them as *consensual models* shared by a particular community of practice such as scientists or chemistry teachers (e.g., Norman, 1983). Here the researcher argues that the scientific models used for chemical bonding including those taught to learners, even at very advanced levels of instruction, do not necessarily correspond to scientific models in the way that scientists would see them. Gilbert, Boulter and Elmer (2000) talk about *teaching models* distinguishing these from scientific models, seeing the former as models (in the case of this inquiry mental models for chemical bonding) that are actually enacted in the classroom. In this inquiry *consensual teaching models* are thus defined, and are seen as contextualised to the educational environment in which this inquiry has been conducted. These consensual teaching models in the inquiry are the mental models that have been socially-negotiated with inquiry participants including secondary school teachers, teaching faculty and the researchers (see 'conceptual theme for the inquiry' below for a description of how we arrived at the specific consensual teaching models for this inquiry).

6) Conceptual Theme for the Inquiry

The conceptual theme for this inquiry is detailed in Figure 1. In developing a conceptual theme for the inquiry the researcher sought to link the theoretical framework to concepts of chemical bonding. Inspection of common chemistry books (including all of those prescribed for use by the participants in this inquiry) reveals that there is considerable discrepancy in the treatment of mental models used to explain chemical bonding. For instance some textbook authors state that "metals have little tendency to form covalent bonds" (Gillespie et al., 1986, p. 491) whereas others state "metals are just covalently bonded solids" ("Metallic Bonding", 1994, p. 1965).

Based on the theoretical underpinnings, the researcher sees the context of inquiry as crucial. The context for this inquiry is the personal lives, including the learning experiences, of the participants. Hence, from a learners' point of view the scientific model for chemical bonding is that enacted in their classrooms or lecture halls. This is the view with which their constructs were considered in this inquiry. The mental models identified in Figure 1 were negotiated with the education stakeholders (see 'methodology' below) and their classification is based on Norman's (1983) typology: namely, the *target system* (the system the learner is attempting to study); the *conceptual model* of the system (an appropriate model for that system); the *users' mental model* (the mental model the researchers were attempting to discern in the inquiry); and, the *scientists' conceptualization* of the target system. This latter item is now reclassified here as the *consensus teaching model* identified above, and the *users' mental model* is seen here as the *learners' mental model*. In fact given the variety of chemical substances used in the inquiry, the researcher identified a series of target models, from which he sought to frame the interpretation of the learners' (or users') mental models (that is, the specific mental models identified in Figure 1 such as *molecular orbital theory*). The target models have been split across three types of chemical substances; namely, metallic, ionic and covalently-bonded substances. This division is not meant to convey the researchers' views of an appropriate classification scheme; rather it represents the rather traditional divisions of chemical substances, and those divisions that were enacted in the classrooms and lecture halls for this inquiry.

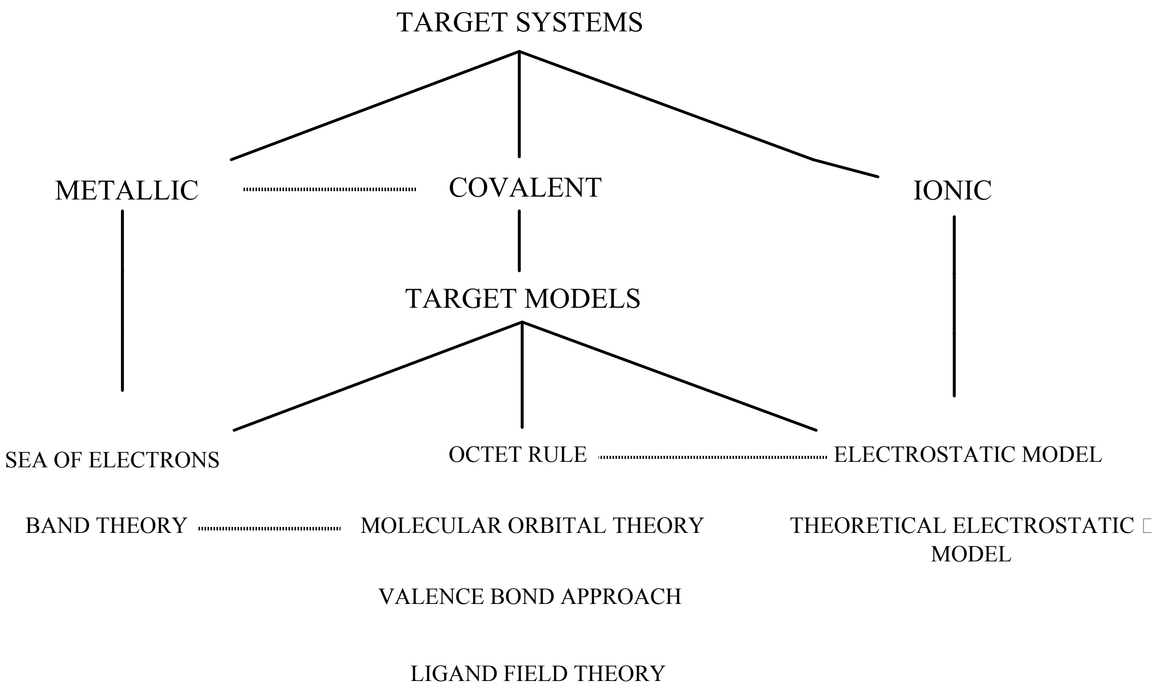

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Figure 1. Conceptual Theme for the Inquiry (after Norman, 1983).

METHODOLOGY

a) Data Collection - Consensus Teaching Models

The first phase of data collection involved developing the *consensus teaching models* described above. Consensus teaching models were developed for each of the target models in Figure 1. This was a complex and intensive process. First, the researcher conducted a detailed examination of lesson plans, lecture notes, textbooks and other curriculum material combined with informal interviews with teachers and faculty. From these he developed a large data corpus and the next step involved the researchers producing a summary of these data resulting in a detailed description of the eight target models for the three categories of chemical substances (that is metallic, ionic and covalent substances). From this was developed *criterial attributes* for each of the target models. Criterial attributes are the essential qualities all of which must be recognized if the model is to be used in a way that is acceptable (in this case to teachers and faculty) (Gilbert et al 1985). Consistent with the theoretical underpinnings these model descriptions and their associated criterial attributes were negotiated with teachers and faculty including four educationalists involved in the teaching of these models to the learner participants of this inquiry and six other specialist chemistry teachers and faculty with no contractual interest in the study, and who were thus independent of the study. Negotiation of model descriptions and associated criterial attributes was an elongated and complex process. This process required these individuals to read the researcher's summary descriptions of the eight target models, and to respond to a proposed list of criterial attributes (suggesting additions to, or omissions from, the original list). Both the model descriptions and criterial attributes varied depending on the educational level. For example, the criterial attributes for the *electrostatic model* at the senior secondary level for the bonding in ionic substances (Figure 1) did not include reference to the ionic-covalent continuum, whereas this aspect was included at for the undergraduate and graduate levels. Similarly, for the target model *molecular orbital theory* (Figure 1), at the graduate level criterial attributes included reference to advanced group theory used to deduce compatibility of atomic orbitals based on symmetry considerations; an attribute not deemed appropriate for undergraduates, and the molecular orbital theory as a whole was not deemed appropriate for secondary school participants. It is important to note at this point, that given the open-ended nature of the interview questions, the use of socially-negotiated detailed model descriptions and criterial attributes, did not 'shoe-horn' a participant (at any level) into a particular mental model; rather, it provided some framework to aid interpretation of discourse.[1] This point becomes more readily apparent when the learners' mental models are described in detail (see research findings below).

The description of these models and their criterial attributes represents the first part of the research findings and these findings are reported below.

b) Data Collection – Learners' Mental Models

Learners' mental models for the target models were interpreted from their expressed mental models. The expressed mental models were obtained from interactive semi-structured interviews which varied in duration from 60 minutes for the secondary school learners to nearly two hours in the longest cases for graduate learners. These comprised a three-step process which was repeated for each of the three target systems (that is metallic, ionic and covalently bonded substances).

The first step involved the interviewer showing the participant a physical sample of a chemical substance (for example aluminium foil, liquid chloroform - $CHCl_3$ - molecular iodine - I_2 - and table salt - NaCl). Common substances were used in order to provide an opportunity to access worldviews that might be in conflict with the consensual teaching models. The respondent was asked to describe the bonding in these substances. In the next step respondents were shown line drawings for each target system depicting a scene or phenomena that involved model use in some way. For example, for metallic substances respondents were show a line drawing that illustrated the high malleability of copper metal (a depiction of a thick block of metal being squeezed through some rollers); for ionic

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[1] In a number of instances, learners' mental models did not match any of the target models, in which case the interviewer simply probed continuously in an attempt to understand the participants' mental model as comprehensively as possible.

substances respondents were shown a line drawing that depicted a large block of solid sodium chloride being crushed into to tiny crystals (and contrasted with a similar sized block of quartz that was not broken down when subjected to the same large force); and, for covalent substances respondents were shown a line drawing showing the (generally linear but sometimes discontinuous) relationship between boiling points and group number from the Periodic Table (seeking to probe their ideas about intermolecular bonding, including hydrogen-bonding). There were two similar line drawings used for each target system (metallic, ionic and covalent) and the drawings varied slightly for the different levels with more challenging examples employed for the gradates (such as the boiling point relationship example described above). The third and final step of the interview consisted of the interviewer showing the learners a focus card that contained common depictions of the bonding for each of the three target systems. These depictions were taken from the textbooks and other curriculum material encountered by the participants in this inquiry. The depictions included illustrations such as ball-and-stick drawings (to illustrate the bonding and structure in covalent substances), and packed spheres (to illustrate the bonding and structure in metallic and ionic substances). The focus cards also included some sophisticated diagrams of, for example, molecular orbital-based depictions of the bonding in molecular covalent substances.

Consistent with the theoretical beliefs described above, the interviewer strived to achieve neutral ground during the interviews in order to reduce potential impact of investigator bias (Johnson and Gott 1996). This research drew on Patton's (1990) recommendations and strived to achieve undistorted communication by, for example, avoiding the use of 'scientific terms' and ascribing the meaning given to scientific terms only the meaning that evolved during interviews (for example terms like 'cloud and 'sharing' that have both common and scientific meanings). The interviewer probed respondents' discourse extensively with neutral follow-up questions (Can you tell me more about that?) and probes, for example, when they introduced common scientific nomenclature like 'ion' and 'sphere', they were asked what shape or charge such 'ion's' might have and how did they see these species arranged in space.

The above three-step interview protocol represents a series of activities and at each step the interviewer continued to probe respondents' views. In this he sought to develop a detailed and fairly complete picture of the participant's mental models for the target systems. He did not seek to impose of push respondents towards an given model, however, when a respondents clearly identified with a specific mental model (that is one of those presented in Figure 1) the interviewer used the criterial attributes for that model as the basis for probe questions. The respondents were also encouraged to draw representations of their mental models and these along with the interview transcripts represented the data corpus for this phase of the data collection. In some cases after viewing their transcriptions interviewees made extensive written comments or alterations, and in a few instances a second follow-up interview was conducted to clarify ambiguity.

c) Data Analysis

Participant-validated transcripts were inspected for statements that revealed participants' views for each of the target systems (metallic, ionic and covalently bonded substances) and their associated target models. These statements were compiled to form an inventory for a given target system, for example, *metallic bonding*: these data were combined with learners' drawings to develop a view of their mental models. When learners identified a specific target model, their views were compared with the consensual teaching models by reference to the criterial attributes for that target model at the appropriate level. In this way learners' familiarity with a given model could be adjudged.

These data were analysed using a *concept profile inventory* (CPI) based on the model employed by Erickson (1979, 1980) and Rollnick and Rutherford (1990). The CPI procedure consists of examination of interview transcripts for expressions and statements that could be construed as evidence for learners' views, in this instance, their mental models for the target systems and target models for chemical bonding. These expressions were summarised and formed the unit of analysis. By examining the entire set of expressions in the transcripts, it was possible to gain a global perspective of the participants' views. These views were then organised into a series of categories which formed a *conceptual inventory* for an individual's mental model. Commonality of views was deduced from examination of the inventories and used to summarise the research findings.

d) Sample

There were two cohorts of participants, about one fifth (across all levels) were from a Western Australian secondary school and tertiary educational institution, the remainder from New Zealand. There were a total of 30 learner participants chosen purposively to provide a reasonably even gender balance, and a range of educational levels and abilities (based on teachers' perceptions for the high school learners, and as deduced from their academic transcripts for the tertiary learners).

The New Zealand Year-13 and Year-12 Australian secondary school learners were all in the final year of their high schooling and aged 16-18 years old. All were contemplating higher education in science, and science-based careers. The males were less confident than the females and generally less talkative. There was a spread in academic ability ranging from some very able learners to some that were finding their school studies rather challenging. All but one of the learners was of European decent; the other learner identified herself as being of Pacific Island (namely Samoan) ethnicity.

The undergraduates were all intending chemistry majors; the New Zealand learners in a conventional three-year bachelor's degree, the Australians in an applied chemistry bachelor's degree. There was an even mixture of second- and third-year learners (of a three-year academic programme of study). The New Zealand learners undergraduate degree was four years long incorporating a total of 12 months work experience: the third-year learners had at the time of interviews done one 3-month work placement and the second-year learners were to do this work placement at the end of their second year. Like their secondary school counterparts, there was a reasonable spread in academic ability for the undergraduates, with some holding outstanding academic records and others struggling to pass their courses. All of the learners identified themselves as being of European decent. The participants were generally confident in nature although the less able learners appeared less confident.

Half of the graduate level participant learners were aged 20-22 years old and engaged in the second, research year, of their two-year Master of Science degrees, and had completed the papers part (equivalent to a postgraduate diploma in science). The reminder consisted PhD candidates aged 24-26 years old from new PhD candidates, through to those in the latter stages of their thesis write up. Given the entry level requirements, not surprisingly, these were academically able individuals. However, even within this cohort there was a spread in academic ability with some participants possessing extraordinary academic records. By the completion of this inquiry a number of these latter graduate level participants had secured faculty positions, some in highly prestigious tertiary institutions. Theses topics varied with the Australian graduate participants generally engaged in research with a more applied focus (e.g., environmental chemistry) and the New Zealanders more 'academic' in focus (e.g., organometallic & structural chemistry).

These were mature, confident individuals with seemingly strongly held views. The interviews were wide-ranging and extensive (see above) and the participants showed little hesitation during interviews.

FINDINGS

There are two parts to the research findings; the consensual teaching models and the users' mental models. I begin with a description of the consensual teaching models and criterial attributes for the target systems (for metallic, ionic and covalently-bonded substances in turn) and consequent target models and criterial attributes, and this is followed by a description for the learners' mental models including their preferences from depicted models presented on focus cards (see methodology). Learners' mental models are then followed by an examination of the completeness or understanding they evidenced for their mental models based on the criterial attributes identified in the first part of the data collection. I conclude by looking at how participants were able to use their mental models to explain a variety of phenomenal depicted on focus cards (also serving as a probe for learners' satisfaction of some of the criterial attributes).

a) Consensus teaching models for chemical bonding

Eight *consensus teaching models* were identified for the three target systems (Figure 1) and the general form of these models is briefly described here.

For metallic bonding the two identified target models were the *sea of electrons* and *band theory*. In the sea of electrons model, the structure of the metal is viewed as being built up by packing like-sized metal atoms to form high symmetry lattices (e.g., FCC = face-centred cubic). The valence electrons are not strongly associated with individual metal atoms and move freely throughout the metal lattice resulting in the formation of positive metal ions. Hence, in this model of metallic bonding the structure consists of metal ions in an infinite array immersed in a sea of mobile, delocalised electrons. Band theory for the structure of metals (and other solids) has a number of similarities to the sea of electrons model. In band theory, metals also form arrays of metal ions and the valence electrons are also delocalised. However, the delocalised electrons are located in a series of energy bands formed from the overlap of atomic orbitals. The interaction between two atomic orbitals of a metal atom results in the formation of two molecular orbitals (that is, orbitals associated with the entire piece of metal) - one low in energy and a second higher in energy. The lower energy levels of the bands are filled with valence electrons and form the valence band - a non-conduction band. The upper energy levels (which in the case of many metals are partially-filled) form the conduction band: the difference between the bands is called the band gap. In metals and other conductors the band gap, if it exists at all, it is very small. Powerful cohesive forces between the metal ions and electrons bond the metal together.

For ionic substances the identified target models were termed the *electrostatic model*, and the *theoretical electrostatic model*. The electrostatic model is based on the octet rule, and although electrons are not directly 'transferred' between metals and non-metals, the metal achieves an octet by losing an electron and the non-metal by gaining an electron. The bond then consists of attraction between oppositely charged ions. Even bonds between atoms with a very large difference in electronegativity are only partially ionic in nature, and it is more appropriate to talk of the ionic character (or proportion) of a bond. The assumption that ionic lattices are made up from arrays of anions and cations in fixed geometrical arrangements means that lattice energy can be calculated from the attractive and repulsive forces present in the lattice, using what we here term the *theoretical electrostatic model*. Each cation (and anion) experiences alternating attractive and repulsive forces at certain fixed distances which are determined by the geometry of the lattice. Thus, the total energy of interaction between the ions in the structure can be calculated from a sum of these alternating attractive and repulsive terms.

For covalent bonding the four identified target models were the *octet rule*, the *valence bond approach*, *molecular orbital theory*, and *ligand field theory*. The *octet rule* is a rudimentary model based on the octet rule of full-shell stability (similar to that described above for the bonding in metallic substances). A complete octet implies full occupancy of the *s* and *p* orbitals of the valence shell. It is energetically unfavourable for atoms of many elements to lose or gain the number of electrons needed to obtain an octet, however, such elements can obtain an octet by *sharing* electrons with another atom: the build-up of electron density between the atoms results in bond formation. The *valence bond approach* has its origins in quantum mechanics. In the valence bond approach the bonding wavefunction resulting from a combination of atomic orbitals can be viewed as linking the two atoms together in a bond. This approach is in many ways similar to the octet rule model and the electrons are assumed to be localised in atomic orbitals between the atoms. *Molecular orbital theory* also is a quantum-mechanically based model used to describe the behaviour of electrons in molecules. The essence of the approach is that combination of wavefunctions from atomic orbitals result in the formation of new orbitals that are associated with the *whole molecule* rather than individual atoms. Some of the orbitals are bonding, and the build-up of electron density in these orbitals binds the molecule together. At advanced levels it is necessary to employ group theory to decide which atomic orbitals may combine based on symmetry grounds and the model, although possessing of considerable explanatory power (e.g., it provides elegant and convincing explanations for the properties of 'problem' molecules like molecular oxygen O_2), is mathematically, and conceptually complex.

b) Criterial Attributes for Consensual Teaching Models for Chemical Bonding

Criterial attributes are summarized in Tables 1, 2 and 3 for the target models most germane to this inquiry. These were the models most commonly identified by the participant learners: namely, *the sea of electrons model*, the *electrostatic model*, and the *octet_rule*. Criterial attributes were produced for all target models and the remainder, omitted for reasons of space, are available from the author upon request.

Table 1. *Criterial Attributes for the Sea Of Electrons Model of Bonding in Metallic Substances*

Level 1	Level 2	Level 3
Lattice structure	Lattice structure	Lattice structure
Electron mobility	Electron mobility	Electron mobility
Alloy-substitutional	Alloy-substitutional	Alloy-substitutional

Table 2. *Criterial Attributes for the Electrostatic Model of Bonding in Ionic Substances*

Level 1	Level 2	Level 3
Ion formation	Ion formation	Ion formation
Ion size	Ion size	Ion size
Ion shape	Ion shape	Ion shape
Ion type/charge	Ion type/charge	Lattice formation
Lattice formation	Lattice formation	Ionic-coval. continuum
Lattice structure	Lattice structure	
Ionic-coval. continuum	Ionic-coval. continuum	
Ion polarisation	Ion polarisation	

Table 3. *Criterial Attributes for the Octet Rule Model of Bonding in Covalent Substances*

Level 1	Level 2	Level 3
Full-shell stability	Full-shell stability	Full-shell stability
Electron pair formation	Electron pair formation	Electron pair formation
Molecule formation	Molecule formation	Multiple structures
Bond directionality	Bond directionality	Bond directionality
Unequal sharing	Unequal sharing	Unequal sharing
Non-bonded pairs	Non-bonded pairs	
Multiple structures	Multiple structures	
Resonance	Resonance	

c) Learners' mental models for chemical bonding

i) Metallic Bonding

There were two physical prompts used to probe users' mental models of *metallic bonding*, aluminium foil and steel wool, and a third prompt was a focus card containing depictions of the bonding and structure in metals. There was clear choice for the *sea of electrons model* for the target system of *metallic bonding* across all academic levels of learner. The learners seemed to see "free" or "mobile" electrons as a key feature of the bonding in metals, and the undergraduates and graduates showed a greater appreciation of the continuous nature of metallic lattices than secondary school learners. The secondary school learners liked the realistic looking depictions Natalie described one as "realistic" but the older learners were more critical of depicted models for metallic bonding with Jenny a graduate commenting that she did not like one of the depictions because it "shows two lithium's together, its showing definite bonds between the atoms". In general, as might be expected, the undergraduate and graduates' explanations were more detailed and complete. Steve, an undergraduate, talked about "a row of monovalent cations in a delocalised sea of electrons", and Kevin a graduate commented that "the electrons are not specifically associated with the atoms as such; they are shared through the whole structure".

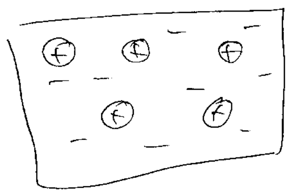

Figure 2. *Kevin's Drawing of the Bonding in Aluminium Foil*

ii) Ionic Bonding

The learner's preferred mental model for the target system of *ionic bonding* is the *simple electrostatic model*, although like the target system metallic bonding, a few learners held mixed models and used concepts from other target models. The secondary school learners saw the bonding as an attraction between charged species which they related to the octet rule. David, for example, said he saw ionic bonding arsing from "attraction between the positive and negative charge" which occurred because "opposites attract" and which he saw arising from "where they donate electrons and receive electrons". There was evidence that the secondary school learners saw such bonding as driven by the octet rule with Keith saying "the chlorine requires one more electron to satisfy itself". A second feature of the secondary school learners' mental models was tied to structural depictions - Keith, like others, seemed to confuse lines indicating the structural arrangement of ions with bonds, "this one here with sodium, it's bonded directly to that [chlorine]". Graduates also saw ionic bonding as octet-rule driven with James saying ionic bonding "the sodium prefers to have a one plus and the chlorine prefers to have a one minus", apparently because of a preference for "a noble gas configuration of electrons". But they placed more emphasis on lattice structure with Jason saying sodium chloride "is a classic cubic structure where you have each sodium and each chlorine surrounded by six [other ions]". Jason also mentioned "there's also repulsions" some indication he may have been aware of a few features of *the theoretical electrostatic model*. There also was evidence that the graduates appreciated the omnidirectional nature of ionic bonding with Brian commenting "there are no actual direct bonds as such. There's just the attraction of charged species".

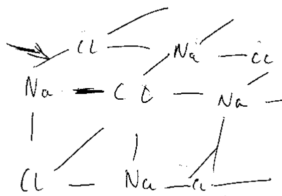

Figure 3. *Kevin's Drawing of the Bonding in Sodium Chloride*

The secondary school and undergraduate learners preferred simple realistic-looking depictions of ionic bonding from those illustrated on the focus card (that is depictions that contained spheres). The undergraduates and graduates in contrast preferred a more complex depiction that illustrated the continuous nature of the ionic lattice more clearly (that is depictions showing an extended array of ions).

iii) Covalent bonding

The learners' preferred mental model for the target system of *covalent bonding* was the *octet rule*. The learners viewed covalent bonding as arising from the sharing of electrons and the driving force behind this process was the formation of a stable octet. The secondary school learners were confused about the bonding in molecular iodine - a common simple view that it involved 'covalent bonding' which involved 'sharing', though what was shared was not clearly articulated. However, they were readily able to discuss the bonding in chloroform and drew diagrams which showed awareness of Lewis structures based on the octet rule (Figure 4). The undergraduates drew similar diagrams and made similar comments,[2] but generally related their bonding models directly to the *octet rule*, for example, Kim commented that they need to "fill up the eight…so they are more stable".

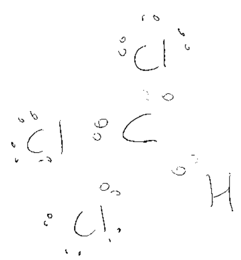

Figure 4. *Neil's Drawing of the Bonding in Chloroform ($CHCl_3$)*

[2] One undergraduate drew and discussed in detail a molecular orbital model for the bonding in iodine – these data are described elsewhere Coll, R.K. (2008, in press).

The graduates evidenced a fuller appreciation of the *molecular nature* of the covalent molecular substances used in the inquiry than their secondary school or undergraduate counterparts. The graduates' metal models also were essentially driven by the octet rule "both iodines are one short of attaining their complete valency in their outermost shell, so by sharing an electron" they both "get the stability of the full shell". They provided similar explanations and drawings to the undergraduates, but predictably introduced more detail, with, for example, Jason talking about "covalently bonded dimmers" which were held together by "van der Waals forces" due to "weak polarisation". Similar diagrams and descriptions were provided for the bonding in chloroform, with Lewis structures being common. Christine held a similar mental model and her drawing shows the dimmers clearly.

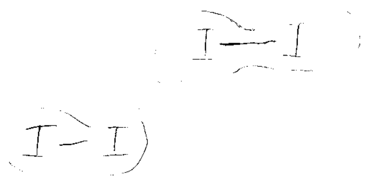

Figure 5. *Christine's Drawing Illustrating Inter- and Intramolecular Bonding in Molecular Iodine (I_2)*

The secondary school learners preferred a more detailed depiction for the bonding of those illustrated in the focus card (one which showed a cyclohexatriene type structure with alternating double and single bonds, and/or individual hydrogen atoms bonded to the ring system) and, unlike undergraduates and graduates, appeared to hold the alternative conception that benzene contains double bonds. The undergraduates and graduates also preferred simple depictions, but showed an appreciation of the delocalisation of bonds in conjugated alkenes and the resonance concept.

d) Learners' Understanding Of Consensus Teaching Models For Chemical Bonding

Few of the participants at any level appeared to possess a comprehensive mental model for *metallic bonding* that was in agreement with the consensual teaching model. The consensual teaching model of the *sea of electrons* possessed four criterial attributes (some of which were addressed above): *lattice structure*; *electron mobility*; *interstitial alloys*; and; *substitutional alloys*. The secondary school learners seemingly had little conception of a continuous metallic lattice, Linda simply saying "it would have a definite structure", but the undergraduate's and graduate's appreciation of the continuous nature of the metallic lattice was more evident and included the use of discipline-specific terminology to describe lattice structure with Bob, for example, talking about "cubic close packing" of the lattice, and Alan about "hexagonal close packed metal ions". This preference also was reflected in choice of depicted models from the focus card, with undergraduates and graduates choosing more open structures that depicted the three-dimensional lattice in more detail, whereas secondary school learners preferred more realistic-looking space-filling depictions (see above). All levels of learner deemed that the bonding in alloys (using steel wool as a prompt) was similar to that of pure metals, but few recognised that steel was an alloy, with Claire saying it "I don't see how its different". A few of the undergraduates and graduates identified that steel contained other metals and non-metals with Steve saying "there would also be a certain amount of carbon in there" and Alan talking about a "mixture of metals".

The learners' understanding of the *electrostatic model* for *ionic bonding* varied depending on level of learner. The secondary school learners appeared to hold a number of alternative conceptions about *ion size* and *ion shape* and had little appreciation of the concept of the *ionic-covalent continuum* or *polarisation of ions*; although the latter concept was not probed directly. Criterial attributes for *electrostatic model* also concerned learners' views for *ion formation*, *ion type*, *lattice structure* and *lattice formation*. Learners offered spontaneous responses for these attributes during their descriptions of their mental models for sodium chloride described above. To summarise these findings; learners across all three levels related *ion formation* to the octet rule of full-shell stability with metallic elements forming positive ions as a result of loss or transfer of electrons and non-metals forming negative ions as a result of the gain of electrons. Undergraduate and graduate learners appreciated that ionic compounds form *continuous lattices* whereas some secondary school learners viewed the structure as molecular in nature. Learners across all levels appreciated that lattice structures were definite and specific to the substance. These latter views were supported by the spontaneous drawing of lattice structures for sodium chloride and in discussions of the depicted models for caesium chloride. Responses for the three criterial attributes not presented spontaneously (namely, *ion size* and *ion shape*, and the *ionic-covalent continuum*), were elicited by discussion of the bonding in lithium chloride.

The secondary school learners were confused about *ion size* with several saying the sodium ion was larger than the chloride. David, for example, stated, "Na would be bigger, and the Cl smaller", and most of the others were uncertain about any differences between sodium and lithium ions, with Keith saying "I don't know, I can't remember". The undergraduates were clear that the sodium ion was smaller than the chloride ion, but their reasons were not very convincing, with, for example, Renee attributing the size chlorine to "an extra electron". The smaller size of sodium was related to the "loss of an electron" according to Keith, and Kim said "chlorine like gained an extra shell, and sodium's lost one". The graduates also were surprisingly uncertain about ion sizes; those getting it right offering the similar explanations to the undergraduates, but four said sodium would be larger with, for example, Grace saying "the chlorine would be smaller because its got more electrons…it's got more attraction running around".

The secondary school learners were unsure about *ion shape* when probed, but their drawings indicated spherical shapes, Neil describing them as "round". The undergraduates likewise saw ions as spherical or round, Phil saying they would be "just circular I guess, sphere, spheres". The graduates saw ion shape similarly, with James saying "it would be more or less spherical".

The secondary school learners saw no difference in polarizing power of the sodium or lithium ions, Anne saying "they are basically the same", although Claire in other discourse alluded to the *ionic-covalent continuum*, saying "the electron will spend most of its time around the chorine", suggesting an appreciation of *unequal sharing* that occurs in covalent bonding. The undergraduates held similar views to the secondary school learners with, for example, one participant Mary saying she thought "it'd be covalent" when discussing the difference between lithium and sodium chloride, and Bob saying "lithium one plus would be a lot smaller than sodium and quite possibly a lot more influencing on the electron cloud of the chloride". Three of the graduates mentioned polarisation explicitly, and related this to the *ionic-covalent continuum*, with Jason saying "if you had your sodium and your iodide or something, you'd have a very strongly polarising cation and a very polarisable anion…so you're probably not going to have strict ionic bonding…you would get more into covalent".

Learners across all levels discussed the preferred target model for *covalent bonding*, namely the *octet rule* spontaneously, and in some depth, during their description of the bonding in I_2 and $CHCl_3$. Hence most learners addressed the criterial attributes for the *octet rule* during this discussion with little or no prompting. Three of these criteral attributes were so addressed and the results are summarised here. Learners across all academic levels evidenced a good understanding of *full-shell stability* and *pairing of electrons*. Although it should be noted that a few secondary school learners appeared to be confused about some aspects of electron pairing, and undergraduate and graduate learners showed a greater appreciation of the concept of *molecule formation* than their secondary school counterparts. The other criterial attributes were evaluated by reference to a focus card which showed depictions of the bonding in benzene (C_6H_6). The criterial attributes for the *octet rule* are different for different levels of learner with secondary school learners not expected to show understanding of *multiple structure* representations or the *resonance* concept.

The secondary school learners showed little appreciation of the concept of *unequal sharing* of electron pairs. The learners described the bonding in $CHCl_3$ in the same way that they did for molecular iodine, namely in terms of the sharing of electrons and full-shell stability. Anne stated that there would "not really" be any difference in bonding and others offered other vague explanations, Neil stated that they "could be different strengths" and Richard that the chlorine atoms were "loosely bonded" compared with the hydrogen. Only two of the learners stated that they saw any difference between the C—H and C—Cl bonds, as a consequence of differences in electronegativity between the H and Cl atoms. Claire and Keith related the difference in bonding to the electronegativities of the hydrogen and chlorine atoms, with Keith, saying, "the electronegativities are different, like the hydrogen and chlorine would have different values…[that's] how much an atom wants to bond with another atom. A high value means it's really eager to get in there and bond with another atom". The undergraduates showed a greater understanding of the concept of *unequal sharing* of electrons than their secondary school counterparts. The undergraduates introduced the concept of electronegativity when asked if they saw any difference between the C—H bond and C—Cl bond. Steve, for example, commented that "there is significant electronegativity so that's [indicating Cl] much more electronegative than the carbon and so you get significant polarity in the bond". Electronegativity was seen by undergraduates as providing a "pulling" or "drawing" of an electron, or electrons, towards the more electronegative halogen atom. The graduates showed a clear appreciation of the concept of unequal sharing of electrons in polar-covalent bonds. Learners related *unequal sharing* to electronegativity of the chlorine atom which resulted in pulling of electrons towards the Cl. Keith comments: "I have drawn them [the electron pair] in the middle of the bond. I wouldn't really consider them purely in the middle of the bond. They are more shifted towards the chlorine atom than they are the carbon…The chloride atom is more electronegative than the carbon atoms is, which means it will attract the electron density to a greater degree".

All of the secondary school learners showed a clear appreciation of the *directional component* to the bonding in the molecular covalent compound chloroform ($CHCl_3$). Claire attributed the shape of the molecule to the arrangement of the electron pairs and the fact that, "being of like charge, they would repel". Likewise, the undergraduates showed a good appreciation of the directional component of the bonding in chloroform; all either drew stereographic projections (i.e., drawings which use visual clues to show bonds behind and in front of the plane of the page), or specifically stated that the atom arrangement in the chloroform molecule was "tetrahedral". However, their reasons proposed for this shape varied considerably. Steve, for example, stated that "the tetrahedral angle of 109.5° minimises steric interaction", whereas Alan simply stated that "the carbon is sp^3 hybridised".

e) Using Mental Models for Chemical Bonding

Two focus card prompts were used to probe users' ability to use their mental models; one depicted a current flowing through a copper wire (contrasting with a non-conductor of a silica rod) and the second the flattening of solid block of copper into thin sheets. There was some correlation between model choice and model use[3] of the sea of electrons model used to explain some physical properties such as conductivity; however, this was not carried over into the explanations of malleability. The learners used the *sea of electrons* model to explain the conductivity of copper, even if it was not their preferred mental model, Claire (Year-13), for example, saying the "electrons are free to move and carry the current", and Steve an undergraduate saying "when you apply a potential to the copper wire it enables the electrons to flow freely in the delocalised sea from one side to another". The learners were generally unable to provide convincing explanations for the malleability of metallic copper, mostly resorting to descriptions of the macroscopic event rather than offering explanations on the microscopic level, with Anita (Year-13) saying "they move" and they have "gotta go because of the pressure". John a graduate was clear that "I wouldn't say you would be compressing the copper atoms together", seeing instead that "you're changing the form", and Jane a graduate likewise commenting that "you have only changed the massive shape". Whilst these descriptions are essentially correct and there was little evidence for alternative conceptions to do with compressing or squashing atoms (except for a few of the secondary school learners), they are not particularly informative and the participants were unable to reconcile the strength of metals with their malleability.

Learners across all academic levels used the *octet rule* based model to explain the conductivity of molten sodium chloride and non-conductivity of a solid block of sodium chloride. Secondary school learners, however, stated that conductivity of molten sodium chloride was due to the presence of "free electrons" rather than ions. In contrast, undergraduate and graduate learners typically asserted that the conductivity was due to the movement of ions, more in accord with the consensus teaching model. Keith (Year-13), for example, said solid sodium chloride was 'a solid block…that holds the electrons from flowing…the molten sodium chloride, " 'cos it's molten, the electrons are more free". The undergraduates attributed the conductivity of molten sodium chloride to the movement of ions, Phil stating 'the ions can move about' and Renee similarly, saying "the molten state will have sodium ions and chloride ions moving about so it can conduct". Non-conductivity was attributed to "no free electrons and no free ions". The graduates held similar views to the undergraduates, although typically providing some deeper insights, Jason saying "in molten sodium chloride the ions are free to move around so the ions will be able to carry the charge from one electrode to another", and Brian saying "in the crystal matrix the ions are stationary, so while there are charged species there they cannot move…in the molten sodium chloride…because is a liquid they are not held in place…so they are able to move to the electrodes".

[3] The fact that a given learner described the bonding in a particular substance like aluminium using say the sea of electrons model, did not mean they necessarily used the same model to explain physical/chemical properties.

The learners across all academic levels inappropriately attributed the friability[4] of sodium chloride to the presence of weak bonds in the ionic compound. Keith (Year-13) saying "the bonds in sodium chloride I don't think are strong", although Claire (Year-13) attributed the friability to repulsion of like-charged species upon dislocation of the lattice "when the force pushes them together these two strongly negative ions will repel each other, same with the positive". They related the hardness of diamond and silica to the strength of bonding and giant covalent network structure, David saying "in the diamond covalent bonding is stronger", and Anita saying "the diamond is all struck together; they can sort of support each other". Similar, but more detail explanations were offered by the undergraduates, Steve saying "you have an infinitely extended network…and the covalent bonds being stronger are harder to break". The graduates also alluded to strength of bonding and network structures with Jenny saying "being stronger they would be harder to break", and Christine talking about an "extended network of bonds".

Few of the learners were able to use their mental models of covalent bonding to explain changes in colour of metal complexes upon changes to the coordination (this in response to a demonstration in which a strong ammonia solution was added to an aqueous copper(II)sulfate solution). Anita (Year-13) saying "the ammonia attracted the copper and that gave a deep royal blue". The undergraduates were equally uncertain Kim stating "I have no idea". A few undergraduates offered explanations based on electronic transitions or the spectrochemcial series, for example, Renee said "ammonia is higher on the spectrochemical series than water, and it would increase the crystal field splitting…the octahedral splitting would be greater for ammonia". Surprisingly, the graduates offered rather vague explanations, saying the ammonia would be more strongly bound, seen in Brian's comment that "the nitrogen bonding to the copper must be stronger".

In contrast most learner from all levels were able to relate *physical properties* such as boiling point and polarity to the bonding and structure of covalent molecular compounds, with undergraduates and graduates specifically relating physical properties to intermolecular forces and hydrogen bonding. The secondary learners were shown a card depicting common school experiment in which streams of liquids pass near a charged rod (CCl_4 went straight, $CHCl_3$ veered slightly and H_2O veered a lot). The explanations were comprehensive and detailed, with virtually all the learners relating the event to polar-covalent bonding. Claire said "there's no effect because [the CCl_4] is not charged…chloroform on the other hand has got those three which is highly polar bonds…the delta negative end is attracted to the positively charged rod…water is quite highly charged because that [the oxygen] is the second most electronegative atom…so you have two polar bonds".

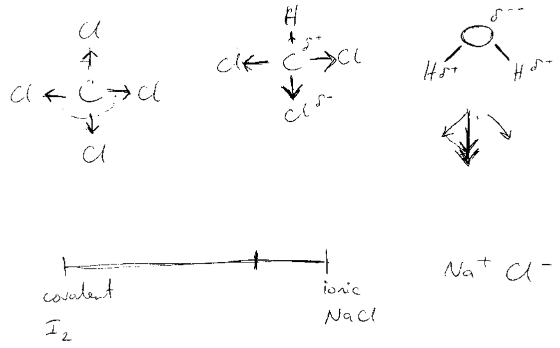

Figure 6. *Claire's Drawing Used To Explain the Nature of Bonding in Chloroform ($CHCl_3$)*

[4] Friable is a common chemical term meaning easily crumbled or shattered.

The task for the undergraduates and graduates was different with the participants being asked to interpret line drawings showing the relationship between boiling points and group-number for a series of hydrides - HF, HCl). The undergraduates indicated they thought the relationship occurred because on increasing intermolecular forces which they attributed to increasing molecular mass: "you're getting to a larger and larger species down the series, there is a larger and larger surface area…and that is facilitating a greater are for van de Waals attractions between the molecules", and Alan saying "they would increase because they are getting bigger". Reasons for the anomalously high boiling points of the first members of group-15 and group-17 series (i.e., HF and NH_3) varied, Steve, Kim and Mary (all undergraduates) stated it was due to them being "ionic in nature". For the ammonia molecule the high boiling point was attributed to "the lone pairs" by Alan, and the others typically speculated: "It could be the electronegativity" said Jane. The graduates were clearer, immediately saying the trends were due to increasing intermolecular forces. Grace, for example, saying "I see it as a size thing, the bigger it is the less volatile". This was the related to polarisation, Grace going on to say "if the compounds end up being polar, they are attracted to one another more so the boiling point is higher". The high boiling points of HF and NH_3 were again attributed to polarisation or hydrogen bonding, James saying "there'd be these dipole-dipole type interactions which make it harder to boil".

DISCUSSION

These data regarding learners' mental models for chemical bonding suggest that learners from all three academic levels prefer simple or realistic appearing mental models of the target systems for chemical bonding. It was not uncommon for learners to hold a number of mental models and more advanced learners typically provided more detailed explanations for the *target models*. In addition, the more advanced learners were more able to be critical of mental models, particularly depicted models presented on focus cards. The extra depth of explanation for the models of bonding by the undergraduates and graduates compared with secondary school learners is most likely simple a reflection of their additional learning experiences. Examination of curriculum material reveals that, as might be expected, undergraduates and graduates have been exposed to a greater range of instruction for the topic than have secondary school learners. Interestingly, for some target systems (e.g., *metallic bonding*) the undergraduates seemed to possess as good an understanding as graduates of the mental models, which may simply be due to their more recent instruction about the model(s) in question.

The findings of this inquiry are consistent with that those of other studies involving abstract chemistry concepts like atomic structure. For example, previous studies found that learners preferred realistic appearing space-filling models of atoms and molecular species (Harrison & Treagust, 1996; Pereira & Pestana, 1991; Taber 1998). The extra depth of explanations of mental models provided by more advanced learners in the present work is consistent with the findings of Kleinman et al. (1987) and, suggests that older learners are capable of an increased level of abstraction and a possess greater number of mental images. Since there is considerable commonality across all three levels of learners, this suggest that learners retain mental models for considerable lengths of time, for example, it is interesting to note that final-year PhD learners retained clear images of the *sea of electrons* model that they encountered nearly 10 years previously. A fascinating feature of the research reported here is the dominance of a reoccurring theme; these participant's mental models seem to be rooted strongly in the *octet rule*. Taber and Coll (2002) suggest that this simple and appealing model dominates secondary school students' mental models for chemical bonding (for both ionic and covalent substances). It seems the notion of 'the atom' and its 'desire' to achieve the 'noble gas configuration' dominates their thinking: a strong focus on the use of the Periodic Table (with its appealing order and structure) may be a factor here. Whilst it is not that surprising that a similar theme was evidence in the present work for secondary school students (from Australia and New Zealand) it is rather surprising that it also was evidenced for both undergraduates and graduates. A conclusion here is that such an observation is evidence of the tenacity of simple, visually-appealing mental models.

Hence, it appears that the mental models preferred by the learners in this inquiry are highly stable in contrast with the claim of Johnson-Laird (1983), and more consistent with the view of Norman (1983). The data do, however, suggest that learners' mental models are incomplete as noted by both Norman and Johnson-Laird. Furthermore, there was evidence that learners' ability to operate or use their mental models, for example, to explain events involving model use depicted on at least some of the focus cards, was limited.

CONCLUSIONS and IMPLICATIONS

The contrast between the models produced by learners compared with those to which they were exposed during instruction is striking in the case of graduates. For example, the rudimentary nature of the *octet rule* is readily evident upon comparison with *molecular orbital theory*. It is important to note that the present work was concerned with learners' *preferred* mental models. Hence, the finding that able and advanced-level learners prefer simple models does not necessarily mean that they have limited understanding of more sophisticated models. What it does suggest, is that these learners prefer simple models, and probably relate to more abstract models only in the context of tests or examinations.

The research reported here suggests that whilst learners prefer simple realistic appearing mental models, senior level learners can utilise concepts from other more sophisticated models - but only chose to do so when their simple explanations breakdown. Smith (1992) and others (e.g., Kleinman et al., 1987) maintain that it is a feature of experts that they appreciate the function of models, and retain multiple images and mental models in their minds to call upon when circumstances dictate this is useful (see, e.g., the discussion about the ligand field theory described earlier in this work).

The results of the present work also point to evidence that senior learners appreciated the limitations of the simple models they preferred to use. For example, the preference for the cyclohexatriene-based structure for benzene (C_6H_6) is not of concern if the learners understood the limitations of the model, and pragmatically choose to use it for reasons of convenience. In doing so, such learners are in fact mimicking model use by experts (Walton, 1978; Weller, 1970). If we want learners to consistently use more sophisticated mental models for chemical bonding, then it seems we need to make a much stronger case for the use of more complex, sophisticated mental models. This might usefully be achieved by the use of discrepant events (e.g., Schmidt, 1997) or prediction-observation-explanation (POE) type activities (White & Gunstone, 1992) that engender cognitive conflict (e.g., Lawson, 1988; Strike & Posner, 1992). Such conflict strategies would drive learners to call upon models that have increased explanatory power. In doing so, we drive learners to act more like scientists. In other words teachers need to emphasise the *purpose* of models; so we can use simple models (like the *octet rule* and *sea of electrons* model) provided we understand their limitations and understand in which circumstances it is appropriate to use them.

There was evidence in this inquiry that some learners' failed to appreciate the limitations of models (both simple & complex models). One danger of encouraging the use of more sophisticated models is that students can come to view models as copies of reality at the microscopic level - especially in the case of physical models like ball-and-stick models or space-filling models (Smit & Finegold, 1995). Harrison and Treagust (1996) caution out that the realistic appearing images from such modern techniques as tunnelling electron microscopy reinforce such notions (along with discourse in textbooks that infer we can 'see' atoms with sophisticated techniques such as these).

The observation that learners *prefer* simple models, whilst likely not the intention of the teachers is not necessarily cause for concern. However, these findings raise the question as to the advisability of teaching sophisticated and abstract mental models for the concept of chemical bonding. If learners across all levels prefer simple models, appreciate the limitations of these models, and are able to modify or add to these models when necessary, is there any purpose to the teaching of complex abstract models? Indeed, some authors suggest that teaching of highly abstract models at the introductory level is counter-productive. Gillespie and co-workers suggest that there is little point in teaching molecular orbital theory to undergraduates, and maintain that it is the concept of the orbital that proves most problematic (e.g., Gillespie et al., 1996a, 1996b). Ogilvie (1990) and others (e.g., Bent, 1984; Shiland, 1999; Tsaparlis, 1997) argue that quantum-mechanical models for molecular structure are unnecessary in undergraduate chemistry. The argument here is that introduction of such models is not accompanied by sufficient evidence their applications to promote acceptance (see also Ogilvie, 1990). This is the classic problem fro higher education teachers; we commonly have mixed classes at first year. Some who intend majoring in chemistry, some who are doing chemistry out of interest, and many who are doing chemistry as service course to support another program such as engineering and medicine. Chemistry learning involves building upon mental models for chemical bonding in order to develop other concepts such as spectroscopy and the development of reaction mechanisms or reaction schemes. Such 'building' upon simpler models is clearly of most value for intending majors, but also of use to say materials and process engineers who draw upon such ideas in advanced engineering study. There are two potential solutions to this dilemma. One is to stream students and have different streams for chemistry for majors, and non-majors. In some cases this may be not feasible; for example, it would involve double teaching of modest-sized classes, which would likely be prohibitive cost-wise.

A second recommendation then is that for teachers to do a serious analysis of chemistry content and make hard decisions about what to include and what not. Universities have more flexibility about content than schools, the latter of whom typically are required to adhere to curriculum statements devised buy external bodies. The latter half of this century has been characterised by enormous advances in science and technology. Scientific and technological innovations have changed the entire nature of society resulting in demand for a more highly-skilled work-force. This demand has led to a large increase in numbers of students studying science in high school and tertiary institutions (Buntting et al., 2006; Coll, 1997; Fensham, 1988). The rapid growth in science and technology has also led to a focus on more applied courses and vocationally-oriented degree programs (Buntting et al., 2006). Whilst this is shift in focus may be appropriate, it does present some difficulties. Buntting and co-workers, for example, suggest that up to 50% of the intake of first year science students lack understanding of key underpinning concepts. A further difficulty is the enormous number of applied science topics now available, and teaching staff are faced with the difficult task of deciding what topics to include in their courses.

Many lecturers are uneasy about leaving out topics that they see as interesting and relevant to students, and there is a tendency to want to include as many topics as possible. However, research into learning and instruction suggests that it may be more beneficial to teach a few topics in depth, instead of trying to give a superficial coverage of a large number of different topics (Eylon & Linn, 1988). Research into instruction and learning provides a deeper insight into how students acquire concept-knowledge and reasoning skills. Eylon and Linn suggest that a key finding of research is that an in-depth coverage of relatively few topics is more beneficial that a more superficial coverage of many topics.

The argument here is that students' need to develop their own concepts, see how to link new concepts with their existing concepts, and develop their own strategies for higher level activities such as problem-solving (Coll, 1997). This, it is suggested is problematic if they are overloaded with factual material, or encounter too much material at once. Eylon and Linn suggest that there are a number of factors that educators need to take into account during instruction: content, organization and presentation of material, the student's level of cognitive development, and the students' level of prior knowledge.

Other recent work in our group (Ishak & Coll, 2006) supports Fensham's (1988, 1994) notion that we need to carefully analyse the content of our courses (or papers) before we teach. Fensham says we need to 'treat content as problematic'. I don't mean here that we think one concept or another is difficult, but that we need to see that the process of deciding what content should be taught to students, at whatever level, is itself problematic. Let me illustrate with an example. When writing a recent book chapter on chemical bonding Keith Taber from Cambridge University and I got involved in a discussion about what constituted the 'scientific model' for covalent bonding (Taber & Coll, 2002). Keith, writing from a secondary school teacher's perspective (in fact a trainer of secondary school teachers), was judging student understanding against a 'scientific model' that was not in fact the currently held model. We ended up realising neither of us was right or wrong, but that at each level of education, we can only teach models (in this case of covalent bonding) at a level appropriate to our target student audience. This applies to secondary school, first-year or masters-level students. So to treat 'content as problematic' here would mean the lecturer making a careful analysis of the content to be taught (here models of chemical bonding) and deciding purposefully which model was appropriate. We might think we do this; perhaps we do by instinct or based on experience. I would argue we need to engage in this to a much greater extent!

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