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Investigation of Secondary School, Undergraduate, and Graduate Learners' Mental Models of Ionic Bonding

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Abstract: Secondary school, undergraduate, and graduate level learners' mental models of bonding in ionic substances were explored using an interview protocol that involved the use of physical substances and a focus card containing depictions of ionic bonding and structure. Teachers and faculty from the teaching institutions were interviewed to contextualize teaching models within the educational setting for the inquiry. These data resulted in two socially negotiated consensus teaching models and a series of criterial attributes for these models: the essential qualities, all of which must be negotiated, if the model is used in a way that is acceptable to scientists. The secondary school learners see ionic bonding as consisting of attraction of oppositely charged species that arise from the transfer of electrons driven by the desire of atoms to obtain an octet of electrons. The undergraduates see the lattice structure as a key component of ionic substances and quickly identified specific ionic lattices for the physical prompts used as probes. The graduates also identified strongly with ionic lattices, were less likely to focus on particular ionic structures, and had a stronger appreciation for the notion of the ionic-covalent continuum. The research findings suggest that learners at all educational levels harbor a number of alternative conceptions and prefer to use simple mental models. These findings suggest that teachers and university faculty need to provide stronger links between the detailed nature of a model and its intended purpose.
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Individuals construct mental representations to interpret personal experiences and make sense of their physical world. From a constructivist view of learning, mental representations, including mental models, are personal representations of a concept or entity that resides in the mind of the knower. In other words, mental models are unique to the observer, and as a consequence uncovering an individual's mental model is not easily accomplished. Individuals

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may behave inconsistently, believing one thing but acting—for example, verbalizing—in a manner inconsistent with their underlying beliefs (Glynn & Duit, 1995). These differences mean that mental models are difficult to explore, elusive and tenuous in nature, and hard to describe. Thus, according to constructivism, we cannot ever be certain we know another individual's mental model because mental models are a private cognitive representation. However, mental models also are placed in the public domain by individuals or groups of individuals: such models have been termed expressed models (Gilbert, Boulter, & Elmer, 2000) and become public models to be used or interacted with—for example, by the scientific or teaching community. When this interaction concludes that the expressed model is of value, it is described as a consensus model (Norman, 1983). Consensus science models that are subject to and survive rigorous experimental testing, published in scientific literature, and widely accepted by the scientific community, are called scientific models. Consequently, despite the personal and subjective nature of mental models, those that are widely accepted by the scientific community become part of the peer-negotiated public language of science, and thereby are deemed to possess a socially accepted meaning (Chalmers, 1999).

Mental Models and Teaching

Mental models as presented by teachers are termed teaching models; these models may be different from the scientific or consensus models. Even advanced-level models taught to graduates are likely different to the model held by leading-edge scientists working actively in the field, the latter which are in fact the scientific models. For example, it is necessary and appropriate to present a complex model for chemical bonding such as molecular orbital theory differently when introducing content in an undergraduate course, compared with the manner in which one would present the model at the graduate level. Teaching models are the models most interesting to us in this inquiry. Gilbert, Boulter, and Rutherford (2000) proposed a template for teaching models, believing that a teaching model should satisfy a number of criteria (Table 1).

These criteria provide useful insights into how we might consider teaching with models and they suggest that teachers face some formidable challenges. We have mentioned the notion of consensual and scientific models; however, teaching models also are socially negotiated. For instance, what faculty at one institution believe are the essential features that make up a particular model may differ from the views of faculty in another institution. Here we wish to introduce an additional category of model, consensus teaching models, and believe that the teaching of mental models endeavors to communicate consensus teaching models to learners. We see such models as contextualized to the teaching institution and sociocultural environment in which they are created

Table 1
Criteria for teaching models

Criteria for teaching models[a]	
Completeness	The entities of which the model is composed and the relationships between those entities should be clearly understood
Coherent	Level of detail of explanation it provides matches the needs of the students
Concrete	The model should be comprehensible to students
Conceptual	The model should form a clear bridge between underlying theory and the phenomena being explained
Correct	The scope of the model should be made clear
Considerate	The model should be linguistically well presented

[a] After Gilbert et al. (2000).

and enacted in classroom teaching. We shall see later in this article that this has implications for interpretation of research reports in the literature and for the research methodology used in this inquiry.

Use of Models in Chemistry and Chemistry Teaching

Chemistry as a discipline is dominated by the use of models. "The discipline of chemistry occupies a special place in science since few of the macroscopic observations can be understood without recourse to sub-microscopic representation or models" (Oversby, 2000, p. 227). As a consequence, chemistry teaching also is dominated by the teaching of models, some from within the discipline, others from other related disciplines such as physics and mathematics. Many chemistry models are built up or derived from other models, with the atomic theory, for example, used to develop ideas of molecules and crystals, but itself derived from a model of the nature of matter (Walton, 1978). A further complication for teaching arises from verbal shorthand and visual clues commonly used by experts and teachers. The scientist, expert modeler, or teacher may forget that he or she is communicating a model, instead presenting a consensus teaching model as if it were a real entity (e.g., an atom) or a proven fact rather than as a well-established theory or model (Treagust, Chittleborough, & Mamiala, 2002; Weller, 1970). The teaching of models and modeling is especially difficult considering that a number of authors suggest that popular textbooks routinely contain alterative conceptions (Fensham & Kass, 1988; Hawkes, 1996; Seifert & Fischler, 2001; Taber, 1995).

Learners' Understanding of Chemistry Mental Models

The research reported in this work seeks to develop our understanding of a group of mental models for chemical bonding. Much prior research in the area of models and learners' conceptual understanding of mental models has been concerned with specific mental models such as the Bohr model of the atom (e.g., Harrison & Treagust, 1996). Such work has typically sought to develop an understanding of learners' mental models and compare these with accepted scientific or teaching models. Reports from the conceptual change literature and alternative conceptions movement, based on such thinking, seem to work from a deficit model. In other words, learners are assumed to come to the classroom (or lecture hall) with alternative conceptions or prior conceptions some of which are wrong or might interfere with their learning of more advanced or sophisticated chemical concepts. Much of the alternative conceptions literature espouses constructivist-based teaching approaches. Some authors dispute the use of constructivist-based pedagogies, and one of the main criticisms of constructivist-based teaching is that it is ontologically and epistemologically muddled [see Matthews (1998) and references therein]. We suggest here that mental model use in chemistry teaching and learning is similarly muddled. Few teachers attempt to explain the nature of models and modeling to students, presumably either from lack of concern or appreciation of the issue, or owing to curriculum pressures (Dagher, 1995a,b). One consequence of this is that teachers and students hold different ontological and epistemological perspectives. Millar (1989, p. 590) pointed out that this issue derives from a particular teaching stance: "The science covered at school is, almost entirely, a consensually agreed body of knowledge. There is, therefore, a limited value in children taking away from science lessons ideas that diverge radically from accepted ones." This teaching stance also is prevalent at the tertiary level where faculty—well aware of the limitations of these teaching models—for the sake of simplicity teach such models as facts in introductory-level courses. Only much later in a student's education do teachers suggest that well-established models may be subject to change. Critics of constructivism argue that this is as it should be, and see little point in negotiating meaning about conceptual models for which there is wide consensual agreement (e.g., Matthews, 1998). There is some evidence that tertiary chemistry teachers see that students need to know more about the nature and purpose of models, and discussion of the nature of models appears in some recent textbooks (e.g., Zumdahl & Zumdahl, 2000).

Investigating Learners Mental Models in Science

Science education researchers investigate learners' (and teachers') mental models by attempting to gain access to their mental models through their expressed models (Boulter & Buckley, 2000; Franco & Colinvaux, 2000). Whereas many researchers recognize that accessing students' mental models is problematic, little attention is paid to the consensual or teaching models used as the basis for such inquiry. It also is important to note that given the personal nature of mental constructs, research findings must inevitably represent the researcher(s)' interpretation of participants' expressed models, and clearly this is mediated by the researchers' ontological and epistemological beliefs, and research tools employed. It is noteworthy that many research inquiries are dominated by the use of a few qualitative techniques, mostly interviews, commonly applied to just one cohort of participants (e.g., students or student teachers). This means that researchers' understanding is based almost solely on participants' expressed mental models, with little appreciation of other factors such as participants' subconscious beliefs.

Many studies reported in the science education literature are concerned with aspects of students' mental models in science and chemistry. Much of this work is involved with uncovering student alternative conceptions and the literature in this area is dominated by conceptual change research (e.g., Pfundt & Duit, 1994, 1997). We describe some of the findings from this body of literature below, with a focus on chemical bonding. Although this research was conducted from a constructivist (or some variant thereof) view of learning, the studies typically assume that there are consensual scientific models or concepts against which student conceptions might be compared. We will discuss this issue in more depth later when we describe the theoretical framework used in this inquiry.

Learners' Mental Models of Chemical Bonding

Chemical bonding is one of the most important topics in undergraduate chemistry and the topic involves the use of a large variety of models varying from simple analogical models to sophisticated abstract models possessing of considerable mathematical complexity (Fensham, 1975). It is hard to overestimate the importance of models and model use in this area. The fact that we cannot see how atoms or elementary particles are held together and how they interact means that scientists and learners who want to understand chemistry need to understand models for chemical bonding. To understand and explain the macroscopic, we need to have a picture or image—a model—of what is going on at the microscopic level. To say we have taught students chemistry, we must have helped them reach an understanding of the fundamentals of chemistry; in other words, the learners must understand chemistry's models. It may not be immediately obvious to nonchemists why models of chemical bonding are so important to chemists and chemistry teachers compared with other chemistry models. However, literally everything in the world is composed of chemicals, the nature of substances, and the changes—both physical and chemical—that these substances undergo, is derived from the nature of the interactions between elemental components of these substances, be they atoms or charged particles such as ions. Whether chemical substances exist as salts or molecules, their melting points, boiling points, chemical stability, toxicity, reactivity—virtually every property of any chemical—can be explained (or at least scientists attempt to explain) using models of chemical bonding.

The nature and sophistication of the models used in chemistry teaching vary depending on the educational level, with students exposed to instruction in increasingly abstract and complex models. Students also are required to interpret a variety of representations for chemical bonds (e.g., chemical formulas or ball and stick models) and chemical bonding is a topic that students commonly find problematic and for which they develop a wide range of alternative conceptions. Remarkably, there is a notable lack of studies of students' mental models for advanced chemical bonding models [see, however, Nicoll (2001)]. A number of alternative conceptions have been reported for chemical bonding (Taber, 1997, 2000, 2001a,b; Taber & Watts, 1997). For example, it is claimed that learners invoke intramolecular bonding in ionic compounds (Taber, 1995, 1998) or believe it is absent in polar molecular substances such as water (Birk & Kurtz, 1999; Griffiths & Preston, 1989). A highly prevalent reported alternative conception is that continuous ionic (and covalent) lattices contain molecular species (Birk & Kurtz, 1999; De Posada, 1997; Peterson, Treagust, & Garnett, 1989; Taber, 1998). Butts and Smith (1987) suggested that the ubiquitous use of ball and stick models used to model ionic lattices may be instrumental in the generation of this alternative conception because learners mistake sticks for individual chemical bonds. The fact that other research revealed that learners believe ionic substances such as sodium chloride possess covalent bonds adds some credence to this suggestion (Peterson et al., 1989; Taber, 1994). In addition, Taber (1997) reported confusion about ionic bond formation and electron transfer, suggesting that some learners believe the formation of ionic bonds occurs as a result of direct transfer of electrons. It appears this view is also held by tertiary-level learners (Oversby, 1997).

Purpose of the Inquiry

The purpose of this inquiry was to gain an understanding of learners' mental models for chemical bonding, with a particular focus on advanced-level university students. As mentioned above, the use of models and modeling is intrinsic to the study of chemistry. Graduate learners in particular need to make extensive use of models for chemical bonding in their research. As such, they are expected to be familiar with current scientific or consensus teaching models and have a clear understanding of what limitations such models possess (albeit within a particular sociocultural context). Hence, the research sought to investigate whether there are preferred mental models for the bonding in ionic substances for secondary, undergraduate, and graduate chemistry learners. We wished to understand how our students' models matured with additional educational experiences, exposure to different curriculum material, discourse, interaction among teaching models and, for the graduate students, their scientific research. In particular, we wished to investigate whether exposure to increasingly sophisticated mental models at different points in a chemistry education shows up in patterns of preference. Thus, we sought to elucidate participants' mental models about the concept of ionic bonding and compare these with the consensual teaching models that are accepted and taught in our classrooms.

Theoretical Framework and Conceptual Theme for the Inquiry

The authors subscribe to a social and contextual constructivist belief system and acknowledge that an individual's constructs are influenced by his or her environment and are subject to influence by prior knowledge, peers, learning experiences, social interactions, and the context in which the learning occurred (Tobin & Tippins, 1993). Our research approach used in this inquiry differs from previous studies in several important ways. First, whereas we accept that models are personal in nature and that mental construction of models is a personal cognitive process, we feel that previous work has not adequately addressed the situated nature of learning and in particular the socio-cultural component of model construction. We wish to develop an understanding of the mental models for chemical bonding for the participants in this study. We recognize that we need to situate our research findings within the context in which the study was conducted, and place more emphasis on the social aspect of social constructivism. The limitations that a given model is deemed to possess, what is right and wrong about a model, and how a model can and cannot be used are socially negotiated. To develop our approach to social constructivism, we have drawn on current thinking from sociocultural learning. Sociocultural views of learning suggest that past research has not paid enough attention to the social mediation of mental construction even in social constructivist–based studies. Wertsch (1991) summarized: "The basic tenet of a socio-cultural approach to mind is that human mental functioning is inherently situated in social interactional, cultural, institutional, and historical context. Such a tenet contrasts with approaches that assume, implicitly or explicitly, that it is possible to examine mental processes such as thinking or memory independently of the socio-cultural setting in which individuals and groups function" (p. 86).

Vygotsky proposed that higher mental functioning is mediated by tools and signs. Of particular importance is semiotic, or sign-based, mediation such as language (Sutton, 1998). Tools and signs such as language are representational in nature and inherently socially situated. The use of language purely for communication is thus too limited because learners use language (and other) cues to determine what represents acceptable discourse. Lemke (1990) suggested that students quickly learn the rules of the game, pick up on teacher cues, and replace common descriptive phrases with more scientific sounding terms such as *refracted* and *reflected* as opposed to *bent* and *bounced*. In other words, learners check their "conformity to (supposed) social norms" (Perret-Clermont, Perret, & Bell, 1991, p. 49) and research suggests that learners' responses and questions in dialogue do not reveal just autonomous cognitive activity, but also attempts to comply with sociocultural norms and expectations.

Methodology

Data Collection

Data collection was composed of two distinct stages. The first stage consisted of a detailed examination of curriculum material (i.e., lesson plans, lecture notes, textbooks, and workbooks used by learners) combined with informal interviews with the instructors involved in the inquiry. The synthesis of these data comprises the consensus teaching model for the target system of ionic bonding (i.e., models for the phenomenon or concept under study—in this case the bonding in ionic substances) (Norman, 1983). From these descriptions, criterial attributes were developed for each target model (Gilbert, Watts, & Osborne, 1985). Criterial attributes represent the essential qualities, all of which must be recognized if the model is used in a way that is acceptable to scientists. This included concepts such as ion size and shape, the formation of an ionic lattice, lattice structure, and so forth. The criterial attributes for a given target model vary depending on the level of the learner. Thus, for example, undergraduates and graduates in the institution involved in this study were expected to be familiar with the concept of the ionic-covalent continuum (i.e., the notion that no bond is purely ionic or purely covalent), and the polarization of covalent bonds, whereas secondary students were not expected to be familiar with these concepts. The teaching models and criterial attributes are clearly socially situated and were developed in collaboration with the teachers and faculty from the institutions in the study, and then further negotiated with six additional independent experts (2 secondary school teachers and 4 tertiary-level instructors). Negotiation consisted of the researchers producing a detailed description for each of the two models, along with a list of the essential concepts required (e.g., ion shape, ion size, polarization). The experts then responded to the descriptions and lists, indicating, for example, concepts they thought were missing or concepts on the original list they thought should be omitted. This was an extensive process with many discussions and substantial negotiation required to reach consensus.

The second stage of data collection involved elicitation of learners' expressed mental models of the target systems, obtained by means of semistructured interviews, including the use of a focus card containing depictions of ionic bonding and structure. Participants' expressed mental models were elicited by interactive dialogue between the researchers and the participants, conducted on neutral ground to reduce the influence of investigator bias (Johnson & Gott, 1996). The researchers sought to access this neutral ground using a number of techniques (Patton, 1990). First, the interviewer constantly worked to ensure undistorted communication took place. For example, words that hold an established scientific meaning (i.e., as negotiated with the stakeholders in the inquiry) were only ascribed the meaning imparted to them in the conversation of the interviews. The interview protocol was composed of three tasks. Two tasks involved showing participants samples of ionic substances (sodium chloride and lithium chloride) and asking them to describe the bonding in these substances. In the third task they were shown a focus card that contained depictions of ionic bonding and structure, and asked which of the depictions they preferred, which they disliked, and why for both options. These items represent focus activities. Each activity was accompanied by extensive probing and questioning based on the criterial attributes. The learners also were encouraged to draw representations of their mental models during the interviews when describing their mental models. The interviews were around 60 minutes long for the secondary school participants and between 90 minutes and 2 hours long for the graduates. All of the participants were provided with transcriptions of their interviews and a number of participants were reinterviewed to clarify ambiguity in descriptions and explanations.

The interviewer used the criterial attributes as a checklist during interviews. Participants discussed their mental models spontaneously based on the physical prompts of sodium chloride and lithium chloride. However, we believed that to rely solely on this might provide a limited or distorted representation of the learners' mental model for ionic bonding. Hence, the focus card and additional physical and verbal prompts (based on the criterial attributes) were used in an attempt to access as much detail about the learners' mental models as possible. Thus, for example, if participants introduced the notion of an ion, they were asked to describe what they thought that ion was like, the size, the shape, and so forth. The use of the lithium chloride prompt illustrates the process. The learners' views of the ionic-covalent continuum and ion polarization were not elicited directly (as this might make the interview appear like an exam and suggest to respondents that they were expected to know about these concepts), but the use of lithium chloride as a prompt, in addition to sodium chloride, was intended to provide learners with an opportunity to discuss these concepts. Because the lithium cation is small and highly polarizing, it induces significant covalency into an ionic bond. Consequently, lithium chloride was chosen as the prompt; because the two compounds (i.e., sodium chloride, lithium chloride) contain a common anion, the intention was that learners would focus on the nature of the cation.

The interview protocol was developed from a pilot study (Coll & Treagust, 2001) and constructed in such a manner that the learners' mental models were elicited in an open-ended fashion. Thus learners described their mental models before they were prompted with other questions (i.e., based on the criterial attributes), and the depictions of the target models were introduced last to reduce the likelihood of these depictions influencing model choice.

Sample

The sample chosen for the inquiry was composed of a total of 24 learners with a gender balance and spread of academic abilities, with 8 chosen from each of secondary, undergraduate, and graduate educational levels. The secondary school learners (aged 17–18 years) were from single-sex schools in a middle-class suburb of a New Zealand City. The undergraduate participants (aged 19–21 years) were intending BSc chemistry majors from a New Zealand university. The graduate learners were from the same institution and were composed of 4 PhD candidates (aged 24–28 years) and 4 MSc-level candidates (aged 22–24 years); these were high academic achievers, a reflection of the entry requirements for graduate studies. This was a convenience sample that reflects the educational context in which the inquiry was conducted. Criteria for selection of participants were purposeful in that we wanted to obtain as much variety as possible, with different education levels and abilities, gender, ethnicity, and so forth. The intention of this decision was to provide the researchers with a spread of participants that reflected the general makeup of the student population in the educational context.

Research Findings

The research findings for the first phase of the study are composed of the negotiated descriptions of the mental models for bonding in ionic substances, situated within the educational context described above. Examination of curriculum material and interviews with instructors from the institutions involved in this inquiry resulted in identification of two target models (Norman, 1983). One model, termed the electrostatic model, is based on the octet rule; another model, termed the theoretical electrostatic model, is based on the computation of the alternating attractive and repulsive forces within an ordered ionic lattice (Cotton, Wilkinson, Murillo, & Bochmann, 1999; King, 1994; Zumdahl & Zumdahl, 2000). Within the context of this study, the former model is introduced at secondary school; the latter model is introduced in the second year of the undergraduate program. The common concepts for both models agreed among the teachers and independent experts are described below.

The meaning accepted by the educators in this inquiry for the term ionic bonding is: a descriptor for chemical bonds between atoms with a large difference in electronegativity (an empirical measure of the tendency of an atom in a molecule to attract electrons) where orbital interactions are not considered important. According to current theory, there is no such thing as a pure ionic bond; each bond between atoms with different electronegativities rests on a continuum between a purely ionic and purely covalent bond. Pure covalent bonds are bonds in which electron pairs are shared evenly by bonded atoms, and pure ionic bonds are bonds in which there is no sharing of electrons pairs. As a crude model, one might say that for a pure ionic bond, one atom loses an electron or electrons and the other gains an electron or electrons. The bond then consists of attraction between oppositely charged ions although loss and gain of electrons is not seen as the driving force for ionic bonding (Chang, 1998; Zumdahl & Zumdahl, 2000). 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 (Cotton et al., 1999).

Learners' Preferred Mental Models for Ionic Bonding

The research findings from the second phase of this inquiry are summarized under two headings: learners' preferred mental models for ionic bonding and learners' understanding of mental models for ionic bonding with each discussed in turn. [Learners' use of their mental models is described elsewhere (Coll, 1999).] The most commonly held view is presented and summarized first in each case, followed by a description of other alternative views held by a lesser number of participants to give a full picture of the views held by learners. Pseudonyms were used to assure respondents of confidentiality of their responses, and verbatim quotations have undergone some light editing to improve readability. There is currently some debate as to the advisability of editing respondents' quotes (Schiffin, Tannen, & Hamilton, 2001) but the authors believe editing as conducted here, such as the removal of filler words such as *um* and *ah* and deletion of repeated words does not change interpretation of learners' expressed models in any meaningful fashion.

Secondary School Learners. The secondary school learners identified ionic bonding as an attraction between charged species. For example, David drew two vertical columns of ions (Figure 1) and related the bonding in sodium chloride to electron transfer and the resultant electrostatic attraction between oppositely charged species: "I know it's ionic bonding and that's where they donate electrons and receive electrons. So the way I would see that is the Na is positive and Cl is negative. So because there's the attraction between the positive and negative charge, they are bonded together, opposites attract."

The secondary school students related their mental models directly to the octet rule of full-shell stability, with Claire, for example, drawing a schematic of the Periodic Table and using this to deduce the relative electronegativities for sodium and chlorine. She then used this to develop her model for the bonding in sodium chloride, stating that "the sodium loses and the chloride gains" because the "chlorine, has a really strong attraction for electrons," whereas the "sodium is holding that one electron in the outer shell really loosely."

The learners' choices of depicted models were consistent with their descriptions given above in that the learners preferred a simple realistic-looking model (depiction A, Appendix A). Aesthetic appeal of the depictions seems to have been a factor, and the learners stated that they found the depiction familiar and simple. For example, Frances stated that "you can still very simply see how it would be," and Claire commented "I like that kind of 3D, it's like what I have seen before." The most disliked depictions were D and E; D was deemed complex and confusing and E was considered unclear, as illustrated by Anne's response that E was "very strange."

Undergraduate Learners. The undergraduate learners' preferred mental model for ionic bonding also was the electrostatic model, but they placed greater emphasis on lattice structure and the use of domain-specific terminology than the secondary school students, as illustrated by Bob's response:

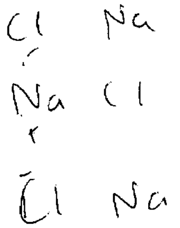


Figure 1. David's drawing illustrating the structure and bonding for sodium chloride (NaCl).

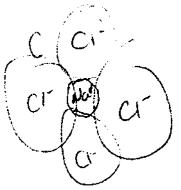


Figure 2. Bob's drawing illustrating the structure for sodium chloride (NaCl).

> OK you have got obviously sodium cations, and chloride anions. Because of the negative and positive charges on either one, the anions tend to be bigger than the cations. The anions pack together in similar ways to the metal atoms in like cubic close-packed or hexagonal close-packed. I can't remember which one they told us it was. Cubic close-packed possibly. Yes, quite possibly cubic close-packed, with sodium atoms located in the gaps [drawing Figure 2]. Like you've got, anions like that, and then another four on top. You are actually going to have a gap in here [draws small circle in middle], where a sodium can fit in there, and then the next one in there [draws another small circle, top LHS].

Bob expresses his knowledge of chemistry and there is a conscious attempt to use the right terms; it seems he feels he is expected to know which form of lattice structure is applicable.

The undergraduate learners' preferred choice of depicted models also was the simple realistic Depiction A (Appendix A), but they were more ambivalent about their choices and more critical of the diagrams, weighing their choices before making a decision. The reason for choice typically was familiarity, Reneé stated, "It's familiar," and Mary said that "You can see what's going on." Two learners chose Depiction C; again familiarity was the dominant reason, with Phill saying, "It looks like one we had in a lecture, it's just familiar," and Mary saying, "I guess, 'cause from this drawing you can see that it's surrounded by eight chlorines." Depiction E was least popular for the undergraduates for similar reasons stated by the secondary school learners: that is, they found the depiction confusing. Kim claimed, "I don't understand it." Alan said that "It's not clear to me," and others expressed similar sentiments. Depiction D also was unpopular with some learners for similar reasons.

Graduate Learners. The graduate learners' preferred mental model for ionic bonding also was the electrostatic model; their reasons were similar to those of the undergraduate and the secondary school learners. Although the graduates exhibited a preference for a simple model of chemical bonding, as might be expected their descriptions were more detailed compared with either of their counterpart groups. Interestingly, they invariably referred to a lattice structure but were less inclined to draw lattice diagrams and less inclined to use domain-specific terminology to describe the nature of the ionic lattice.

> Brian: Well the bonding in sodium chloride is what I know to call ionic bonding. Which involves like a matrix of chloride ions, that's Cl minus in sort of sheets. Well, not sheets but sodium plus ions in a nicely ordered crystal matrix with basically one-to-one ratio of chlorine and sodium, but they are all arranged sort of [drawing rows of Cl^- and Na^+ (Fig. 3)]. Sort of like that, but with sheets stacked on top. Although they are not really in sheets they are just sort attached to, they are just one big mass. So yeah, there is a positive charge with the sodiums attracted to the negative charge of the chlorines, and so on, so overall it doesn't have a charge.

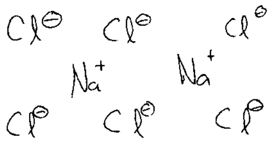


Figure 3. Brian's drawing illustrating the structure of sodium chloride (NaCl).

Interviewer: So can you just think a little bit about the arrangement of those Cl minuses and Na pluses that you have drawn there? Can you just tell me a bit more about how you see them being arranged?

Brian: Well, each sodium is effectively surrounded by chlorines. The chlorines are very large, and sodium is quite small. So it's really a whole lot of chlorines in a fairly close-packed sort of arrangement, and the sodium atoms sit in the holes between the chlorines. So every chlorine is surrounded by sodium[s] and every sodium is surrounded by chlorines.

There are subtle differences in this discourse compared with the undergraduates (Bob, for example). Brian talks about close-packed lattices; this is a general term used to describe lattices in which the packing of ions is efficient (i.e., there is a low proportion of empty space) but it is not specific in the way that the term cubic-close packed or hexagonal close-packed which refer to particular arrangements. The reluctance of the graduates to draw structures of specific lattices was likely because there is a large gap between their instruction and the timing of the interviews. This time gap would no doubt undermine learners' ability to recall specific details of lattice types for, say, sodium chloride and lithium chloride that formed the focus of these discussions.

The graduates related the formation of ions to the octet rule with, for example, Christine stating, "The sodium is losing an electron from its outer shell," and James mentioning the concept of the noble gas configuration: "Its electron configuration, the sodium prefers to have a one plus and the chlorine prefers to have a one minus. It's just filled, having a sort of noble gas configuration of electrons. It likes to have all the electrons paired up so sodium loses one and chlorine picks one up."

In this inquiry, only one of the graduates, Jason, provided a spontaneous response that exhibited knowledge of the theoretical electrostatic model. His description of the bonding in sodium chloride was essentially the same as the other learners: that is, the electrostatic model:

> A chlorine has gained an electron from the sodium atom so that the chlorine atom has a negative charge. The sodium has a positive charge. It's like this structure is essentially held together by electrostatic interactions. Now there's also repulsions as well, because in this area here you also have another chlorine atom which is reasonably close to that chlorine atom so there's repulsions between the two.

However, Jason also introduced the notion of inte-anion repulsion, which has its origins in the theoretical electrostatic model.

The graduates' choices of depicted models were different from those of the secondary school and undergraduate learners; most graduates preferred Depiction C. The graduates liked the spatial aspects of Depiction C and the fact that the diagram appeared to reinforce the continuous lattice structure of sodium chloride, as seen in Grace's response, "You can repeat like, you can see that there's one in the middle, and they are all around it." The graduates were highly critical of the diagrams and appeared to show greater appreciation of visual clues. For example, Brian chose Depiction C and spontaneously offered an interpretation of the dotted lines: "Those dotted lines are a bit of a fallacy because there are no actual direct bonds as such. There's just the attraction of charged species. So I guess A is good in that respect because it doesn't show direct bonds, it just shows a pattern of atoms. But I think C is good because it shows the size better." The distinction made by Brian here is subtle; that is, it is evident that he views the attractive forces between ions as omnidirectional rather than directional. Depiction E was least popular for reasons similar to those of the less experienced participants: that is, unfamiliarity or perceived lack of clarity, with James describing it as "pretty funny," Grace stating, "It doesn't really look like bonding," and Kevin saying that "It doesn't automatically spring to mind what it is referring to." The ability of the graduates to discuss their views of bonding more critically is further exemplified by Jason's response that he disliked B the most because "I think it contains potentially misleading information, especially the lines which are drawn here [indicating intersecting lines at the front of Depiction B on the focus card (Appendix A)], which I don't think mean anything."

Learners' Understanding of Mental Models for Ionic Bonding

As described above, 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 nonmetals forming negative ions as a result of the gain of electrons. The undergraduate and graduate learners appreciated that ionic compounds form continuous lattices, whereas some of the secondary school learners viewed the structure as molecular in nature.

Learners' Views of Ion Formation, Ion Type, Lattice Formation, and Structure. The secondary school–level learners seemed to hold a variety of views about ionic size; a number of the learners asserted that the chloride ion is larger than the sodium ion; however, others believed that the sodium ion was larger. David, for example, stated, "Na would be bigger and the Cl would be smaller." Richard said, "I say the sodium is the larger one and the smaller ones would be the chloride." Others seemed unsure of ionic size. Anne stated that "I can't remember which way around it is," and Frances said, "I think chloride's bigger than sodium. I am not sure. I think chloride is bigger." The secondary school learners failed to comment on the size of the lithium ion; the sole comment from Keith, who seemed uncertain about relative ion size, was that "Lithium would be bigger. It'd have more protons and electrons. It'd be bigger. I don't know if it would be bigger, smaller maybe. I don't know. I don't remember." The tentative nature of the learners' discourse, in which they used expressions such as "I say," "I can't remember," and "I don't know," testifies to their lack of confidence about this aspect of their mental models.

The undergraduates were more confident about ionic size for sodium and chloride ions. With few exceptions, they stated that the sodium ion was smaller than the chloride ion and, moreover, provided explanations for their assertions. Bob stated, "Because you've got a greater negative charge floating around the outside of the small positive charge in the middle, there's a slightly higher amount of repulsion amongst the electrons pushing them apart, making it bigger." Although the undergraduates offered explanations for the larger size of the anion chloride, they did not offer particularly convincing explanations for the difference in sizes of the sodium and chloride ions. Alan, for example, stated that "I've always been told the sodium ion is smaller and the negatively charged ion is slightly larger." Others related the smaller size of the sodium ion to conceptions such as shell and loss of electrons, Reneé stated that "The sodium ion has a reduced radius from the neutral atom because it's got less electrons." Kim said, "Chlorine's, like, gained an extra shell and sodium's lost one." Most of the undergraduates commented on the size of the lithium ion in relation to the sodium ion when discussing the bonding in lithium chloride. Four stated that the lithium ion was smaller: for example, Bob said, "It will be a lot smaller than sodium." The others appeared to believe that lithium ion was larger than the sodium ion; Alan stated, "I would consider lithium to be slightly larger than the sodium." Mary was uncertain, stating, "Because it's exactly the same charge . . . maybe it could be a little bit bigger . . . maybe a little bit bigger than sodium, the lithium." The dialogue here seemed to be partly driven by the interview protocol. Mary is uncertain (as indeed were several of the candidates). Her reasoning seems to be a response to the prompt question rather than her expression in attempting to articulate a clear mental picture. She is trying to recall some details and seems to be groping for ways in which the two ions might be seen as different.

The graduate learners were also unsure about the relative sizes of the sodium and chloride ions. Five of the learners stated that the sodium ion is smaller than the chloride ion, for reasons similar to those provided by the undergraduates. However, others held different views; for example, Grace stated: "The sodium ion is larger than the chloride. The chloride would be smaller 'cause it's got more electrons. It's got more electrons than protons so it's heaps smaller," and Rose commented, "The sodium is larger and the chloride is packed around it." Rose likely confused the packing arrangements. Large physical space–filling models are commonly used in the classrooms in which she was taught about ionic bonding; such models do not differentiate between the ions and the student is expected to pay attention to the teacher's descriptions. Their ability to recall may be an important factor in this alternative conception.

Learners' Views of Ion Shape. The secondary school learners seemed unsure of the shape of sodium and chloride ions, although most of them drew circles or spheres when constructing diagrams of sodium chloride and only one learner, Anita, explicitly stated that she saw the ions as circular or spherical, describing ions tentatively as "probably little balls."

The undergraduates typically described sodium and chloride ions as spherical or circular, as illustrated by the Phill's response of "just circular I guess, spheres." Some of the undergraduates used terms from other concepts of bonding, typically the molecular orbital theory. For example, Bob introduced the concept of orbitals in his explanation of the shape of sodium and chloride ions: "Because all of the orbitals are now filled, there is a certain amount of symmetry there. It's got the 3s as well as the 2p, so it's symmetrical in shape. I have always thought of them as being spheres. Basically that's always been the image that we have been given. But just thinking about it now, because the 2p have formed sort of fuzzy lobes, it's difficult to see that they can sort of merge together and form a sphere."

The graduates, like their undergraduate counterparts, viewed sodium and chloride ions as spherical in shape; for example, James claimed, "It'd be more or less spherical," and Christine said, "I think of sodium plus as a round ball." This part of the interview focused on the shape of the ions. Hence, although these comments suggest a realistic-looking mental model, they may also be a result of spontaneous generation of analogy; that is, the shape is seen to be *like* a sphere or a ball.

Learners' Views of the Ionic-Covalent Continuum and Ion Polarization. The secondary school learners universally believed there was little difference in the bonding in lithium chloride and sodium chloride. It seems that this view was related to the notion that they are both univalent ions. Anne, for example, stated that the bonding was "basically the same, 'cause lithium is one plus, the same as sodium." Probe questions about differences in the bonding in lithium and sodium chloride failed to produce further detail.

The undergraduates' descriptions of the bonding in lithium chloride centered on the relative sizes of the lithium and sodium ions. The undergraduates seemed unsure what the significance of the size difference would have for the bonding in lithium chloride. They did not really offer explanations, as seen in Alan's response: "I basically see the bonding to be the same." A similar situation existed with respect to polarization. Interestingly, only one of the undergraduates, Bob, spontaneously introduced the concept of polarization during his description of the shape of the chloride ion: "The chloride is a big, floppy type of thing. The lithium one plus will be a lot smaller than sodium and quite possibly a lot more influencing on the electron cloud of the chloride." Despite its rather informal connotations, the term *floppiness* is a term routinely used in classroom teaching and textbooks to convey the notion of polarizability, the ease with which the electron cloud is distorted by a powerful electric field close by. Clearly this image stuck in Bob's mind and was one he felt able to articulate easily. The use of domain-specific terminology characterized much of Bob's discourse (e.g., his use of *orbitals* and *cubic close-packed*), which suggests that he in particular wanted to be seen to know science, by using and introducing scientific nomenclature at every opportunity.

The graduates' responses to the lithium chloride prompt were similar to those of the undergraduates, with the most commonly held view being that the size of the lithium ion was the main difference. Interestingly, the graduates felt that this would offer little influence on the bonding. For example, Grace stated that "The lithium is positively charged, and the chloride negative, and I don't see any difference." However, three of the graduates mentioned polarization, some spontaneously going into considerable detail. Jason said:

> I kind of regard polarizability as sort of the floppiness of the anion [respondent laughs]. It's sort of big and easily deformed. I guess I sort of associate it with the softness of the anions as well. If you have a polarizing anion, ah, cation, the cation would be small and highly charged and so it would have a tendency to distort the electrons that are near by, of the nearby anion. So, for example, if you had your sodium and your iodide or something, you'd have a very strongly polarizing cation and a very polarizable anion. So you're probably not going to have strict ionic bonding like you have here, quite a different thing altogether. That's when you would get more into covalent [bonding] with the sharing of the electron.

Jason has used domain-specific terminology: *floppiness* and *softness* (the latter also in common usage and specified in certain bonding theories). He was an able, confident participant and his use of such terminology was different from that of Bob, for example. Jason may have assimilated the practice of using scientific nomenclature; his use of such terminology was automatic and persuasive, whereas Bob's appeared more deliberate and influenced by the conduct of the interview.

Summary and Discussion

Model features and differentiation of models across educational levels are summarized in Tables 2 and 3 and offer insights into the participants' mental models for the target system of ionic bonding. As we suggested at the beginning of this report, gaining an understanding of these learners' personal mental constructs is problematic by its very nature. Hence, it is appropriate for us first to evaluate the methodology employed to understand to what extent we are able to satisfy ourselves that the interviews and focused discussion that formed the discourse between researchers and participants enabled respondents to show what they know in viable ways.

Table 2
Summary of model features and model differentiation for the models in the inquiry

Academic Level	Model Features	Model Differentiation
Secondary school	Attraction between oppositely charged species	Key feature of mental model at this level
	Octet rule based	Seen as the sole driving force for formation of ionic bonding
	Transfer of electrons	Seen as automatic consequence of octet rule
	Realistic pictorial representations preferred	Related to spheres, balls, and generally concrete examples; little evidence of response to visual clues on pictorial representations
Undergraduate	Attraction between oppositely charged species	Seen as the principal driving force for formation of ionic bonding
	Specific cations and anions identified	Rapid identification with specific substances
	Lattice structure emphasized	Seen as key feature of ionic bonding at this level
	Specific lattice structures identified	Quickly attempted to identify lattice with specific substances
	Some appreciation that ionic bonding represents part of an ionic-covalent continuum	Some appreciation of underlying nature of ionic bonding
	Realistic pictorial representations preferred	Related to realistic images, rather than specific artifacts; some evidence of response to visual clues on pictorial representations
Graduate	Attraction between opposite charged species	One instance of participant seeing ionic bonding as being a combination of attractive and repulsive forces within same lattice
	Octet rule based	Routinely mentioned, but not seen as principal driving force
	Lattice structure emphasized	Rapid identification of specific lattice structures, but not typically identified of linked with specific substances
	Specific cations and anions identified	Generally attempted to identify ions with specific substances
	Some, but limited, identification of specific lattice structures	Generally attempted to identify lattice with specific substances
	Ionic bonding represents part of an ionic-convalent continuum	Increasing appreciation of underlying nature of ionic bonding
	Pictorial representations that emphasized continuous nature of lattice structure preferred	Seen as principal identifying characteristic of ionic substances; more critical of pictorial representations—make value judgments of pictorial representations; evidence of response to visual clues on pictorial representations

Table 3
Criterial attributes for models in the inquiry

Academic Level	Criterial Attributes for Electrostatic Model for Ionic Bonding[a,b] Ion Formation	Ion Size	Ion Shape	Ion Type/ Charge	Lattice Formation	Lattice Structure	Ion-Cov. Continuum	Ion Polarization[c]
Secondary school	C	A,AC	C,AC	C	A,AC	A,AC	A,AC	A,AC
Undergraduate	C	C,AC	C,AC	C	C,AC	C,AC	A,AC	A,AC
Graduate	C	C,AC	C,AC	C	C	C	C,AC	A,AC

Note. C = participants clearly identified this criterial attribute in their model descriptions; A = ambiguity in description of this criterial attribute, or little or no evidence in discourse or drawings that the participants identified this criterial attribute; AC = a number of the participants harbored alternative conceptions for this criterial attribute.

[a] Criterial attributes represent the essential qualities, all of which must be recognized if the model is used in a way that is acceptable to scientists.

[b] Only one participant in this study identified a model other than the electrostatic model.

[c] Not all criterial attributes are expected for each educational level; secondary school participants not expected to understand concept of the ionic-covalent continuum or ion polarization.

The detailed description of the data presented above is a modest sampling of the data gathered and represents the researchers' attempt to interpret the expressed models for these participants. We have presented our findings by detailing the concepts held by most participants, and then illustrated the variety of views and richness of data by providing snippets of other concepts (including alternative conceptions) held by some participants. There was high commonality of views across all educational levels, the predominant difference being the greater detail provided by more senior students (commonality and differentiation between models is described below). Despite this latter observation, the interview protocol was probing enough to uncover a large variety of alternative conceptions across all levels [details of which are reported in Coll & Taylor (2001a,b)]. The richness of the data presented here and the sheer variety of views about aspects of the bonding in ionic compounds, along with a variety of model-based explanations provided for the macroscopic events depicted on the focus cards (the results of which are reported elsewhere) (Coll, 1999), suggest that we have achieved a reasonably comprehensive understanding of these participants' views on the concepts under investigation.

The secondary school students' mental models are dominated by the view that ionic bonding consists of attraction of oppositely charged species. The formation of ions occurs through electron transfer; this is in turn driven by the octet rule of full-shell stability. The preferred pictorial representation is that of a realistic appearing model which contains balls or spheres. Hence, the mental model possessed at this level is simple and realistic in nature. It seems that the students feel this model possesses adequate explanatory power appropriate to the circumstances in which their views were probed (i.e., in the interviews). In other words, this model (with its constituent features) works for these learners. Taber and Coll (2002) suggested that this type of thinking dominates views of chemical bonding at the high school level, where models based on atoms (as opposed to molecules, for example) and the octet rules are deemed powerful and appropriate. Model comprehension was limited and there was a wide range of alternative conceptions identified for the secondary school learners, including simple notions such as ion size and shape. The most prevalent alterative conception concerned perceptions of molecularity for the lattice (Table 3).

The undergraduate students' mental models are dominated by the notion of the ionic lattice, seen as a key feature of ionic bonding at this level with attraction of oppositely charged species seen as the driving force for formation of ionic bonds. This contrasts with the secondary school learners, who saw the octet rule as the main driving force. Learners at the undergraduate level recognized the specificity of lattice structures and provided details of particular ionic structures. Realistic pictorial representations also were preferred, but these were less likely to be related to specific artifacts such as balls and spheres; such representations were, however, seen as copies of reality. Alternative conceptions were prevalent at this level, with the most common again tied to simple ideas to do with ion size, and so forth. A few (though much fewer than for the secondary school students) held alternative conceptions about molecularity for the lattice structures.

The graduate students saw the continuous nature of lattices as a crucial feature of the ionic substances although they did not immediately associate this with specific ionic lattices for the substances used as probes. This was emphasized by their preferences for pictorial representations that depicted continuous lattices. It is likely that their inability (or lack of willingness) to identify specific lattice structures is as a result of the timing and context of the inquiry. Many of the undergraduates had completed a course in second-year inorganic and structural chemistry just before the interviews and the third-year undergraduates would have done the same course in the previous year. In contrast, it would have been at least 3 years since any of the graduates had done this course. As a consequence, the undergraduates would likely have remembered specific lattice structures more easily—or at least been more confident about recalling them. The graduate level was the only level at which the notion of the ionic-covalent continuum seemed to be well understood. It is also notable that the graduates spontaneously critiqued pictorial representations and had a greater appreciation of visual clues on the diagrams. Alternative conceptions were generally less prevalent at this level although, surprisingly, a few participants seemed to hold alternative conceptions about simple ideas.

Implications for Teaching

The summary of research findings presented above is contextualized to the educational setting in which the inquiry was conducted. Only the reader can judge whether these findings and our interpretation are pertinent to their own setting. We have attempted to describe the context in which we conducted this inquiry in sufficient detail to facilitate the transferability of these findings (Guba & Lincoln, 1989, 1994; Merriam, 1988). The research findings summarized in Tables 2 and 3 enable us to make recommendations, including specific suggestions about content. These recommendations are based on the criteria proposed by Gilbert, Boulter, and Rutherford (2000) (Table 1). First, we note that models for ionic bonding have been presented well linguistically: The content contained in the written lecture material and textbooks is well presented and consistent. It is not appropriate for us to comment on specific teaching strategies, given that we did not conduct classroom observation (although the curriculum material offers some insights).

Recommendation 1: Emphasize the Link Between the Macroscopic and Microscopic Levels and Use This to Explain the Nature and Purpose of Mental Models in Chemistry

The present work, along with previous studies, implies that students do not easily follow shifts between the macroscopic and molecular levels (Johnstone, 1991; Selley, 1978; Tsaparlis, 1997). It is of some concern that the participants in this inquiry harbored limited understanding and indeed a number of alternative conceptions for aspects of their mental models of ionic bonding (e.g., confusion over ionic size and limited appreciation of the notion of the ionic-covalent continuum). As mentioned above, it seems that the students in this study are reluctant to give up their simple models and cling to them, along with retaining some alternative conceptions even in the face of a model breaking down and its inadequacy being evident. This strongly suggests that they fail to see a link between the theory of the model and the use, or practicality, of the model—for example, as a tool for explaining macroscopic events or properties. Hence, it is recommended that teachers provide clear links between the introduction of models (and the concepts associated with their introduction) and experimental data.

Recommendation 2: Provide More Convincing Justification for the Use of Advanced Mental Models

It is not clear whether enactment of the consensus teaching models in this inquiry provides a clear bridge between theory and phenomena or whether they are coherent and match the needs of the students. The fact that the participants seemed reluctant to change their models suggests otherwise. These learners ostensibly see little need to use more advanced models and concepts to explain aspects of the bonding in ionic substances (such as polarization). This observation suggests that learners remain to be convinced of the need to use more sophisticated models. The learners in this inquiry used the simplest models and concepts necessary to explain the bonding in, and the properties of, ionic substances, although in some cases they had experienced many years of instruction in complex abstract models; they preferred simple, realistic-appearing mental models. In some cases many years have passed since the participants were exposed to instruction of these simple models. These research findings suggest that these participants see their model as correct (from the students' perspective) which indicates that the limitations of the simple models are not apparent (as evidenced by their alternative conceptions). Teaching faculty need to show students that these simple models, although helpful and indeed perfectly useful in some contexts, have significant limitations which restrict their application. Learners, nonmajors and majors alike, need to be able to select appropriate mental models from their repertoire and be able to use these to explain macroscopic events. It seems unlikely that they will perceive a need to select a model (as opposed to retaining or focusing on the simplest, most appealing model) unless they see clear need and justification for doing so. Hence, teachers need to provide more detail about the limitations of the model and elucidate the particular circumstances in which to use a given model.

Recommendation 3: Examine Tertiary-Level Curriculum for Appropriate Content

Gilbert et al. (2000, p. 207) stated that "a teacher should only introduce a teaching model where there is evidence that it is needed." We concur and propose that it may be more beneficial to teach less conceptually difficult content about ionic bonding at the introductory level: in other words, deliver a curriculum that is more appropriate for nonspecialist chemistry majors. In some institutions that have large entry-level or freshman classes, it may be appropriate to provide different streams for majors and nonmajors, but for many institutions this is not practicable. For these latter institutions, we recommend careful examination of content—particularly for advanced mental models—at the early years of the baccalaureate degree program. Teaching faculty need to be critical regarding the value of inclusion of some course content on ionic bonding. This issue applies particularly to the theoretical electrostatic model, which was rarely used by the participants in this inquiry. The model involving the use of moderately complex formulas to the computation of forces seems to be of dubious value even for those who advance in chemistry, and probably should be omitted from undergraduate teaching courses entirely.

A second, alternative, recommendation is that this model of ionic bonding is better taught only at final stages of the degree program.

Recommendation 4:Identify and Address Specific Alternative Conceptions

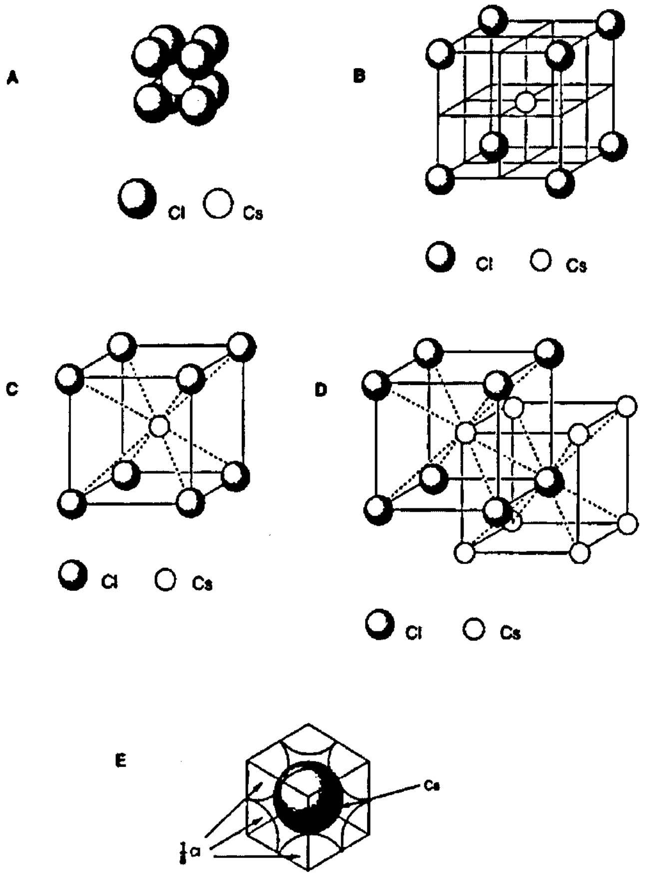
We have written in detail elsewhere about the alternative conceptions for the participants in this inquiry (Coll & Taylor, 2001a,b; Coll & Treagust, 2002). It seems likely that at least some of the alternative conceptions described here and in our other work are present in other educational contexts. The occurrence and prevalence of alternative conceptions were surprising to us and we think teaching faculty need to be more conscious of the possibility of alternative conceptions for advanced-level learners. The amount of content that graduate student has encountered by the time he or she completes a degree is formidable. This is likely part of the problem, but in our view alternative conceptions also are likely when the student does not attribute details much importance: Does it matter if I am a bit hazy on some details, a student might well ask? Yes, it does, and more so in some cases than in others. The significance of ion size, for example, should be related directly to the notion of covalency. In other words, rather than simply noting that the lithium ion is small (which might not be seen as particularly significant by learners), this fact should be related to its polarizing ability.

The case of the ionic-covalent continuum is interesting because this is a plausible concept, but its use is seldom linked to any conflict or failure of any other model. The notion of complete electron transfer that forms part of a simple octet-rule–based model may be deemed inappropriate by teachers, but students need to be made aware of consequences of the failure of such a simple model. This type of problem has been reported previously in the literature for secondary students. For example, Year 12 Australian students, when asked about sodium chloride, suggested ions were formed by the transfer of an electron or electrons (Butts & Smith, 1987). This, it was posited, led them to conceive of molecules of NaCl (as was also evident in the present work). This notion of the molecular nature of sodium chloride was then offered by the students as a reason why solid sodium chloride did not conduct electricity, and linked to the belief that ions were only formed upon dissolving of salts.

Recommendation 5: Take Care with Visual Clues and Make Use of Combined Manipulatives

Teachers need to strongly emphasize the significance of visual clues in diagrams. The dotted lines in some lattice diagrams, used to indicate spatial relationships, are confusing to learners and probably should be omitted as it seems they lead some students to think there are directional bonds between ions rather than omnidirectional forces of attraction. It should be strongly emphasized that the balls and spheres shown in pictorial representations are not images or copies of ions (or atoms) as some participants seemed to think.

University teachers often use a physical model to emphasize aspects of structure. It is common to use large physical models that show the continuous nature of lattices. We strongly recommend such physical models, given that there were widespread alternative conceptions of the molecularity of lattices at the secondary school level. However, teachers should be particularly cautious when using models of ionic lattices that suggest ions are similar in size. Specifically, we recommend that only models which show a reasonable representation of relative ionic size be used. Otherwise we might improve students' understanding about one aspect of bonding (i.e., the nature of the lattice) but inadvertently introduce or strengthen another alterative conception (i.e., confusion about ion size).



Appendix A.

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