Secondary Students' Mental Models of Atoms and Molecules: Implications for Teaching Chemistry

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This interview-based study probed 48 Grade 8–10 students' mental models of atoms and molecules and found that many of these students preferred models that are both discrete and concrete. Modeling is a powerful skill that defines much of the scientific method; however, most younger science students have difficulty separating models from reality. Language that is common to both biology and chemistry (e.g., nucleus and shells) is a major source of confusion for some students. Several students concluded that atoms can reproduce and grow and that atomic nuclei divide. Electron shells were visualized as shells that enclosed and protected atoms, while electron clouds were structures in which electrons were embedded. These, and other alternative conceptions may be generated during discussion as a result of semantic differences between teacher and student language. Students expressed a strong preference for space-filling molecular models and their conceptions of the models used in chemistry reveal much about the difficulties that students face as they try to assimilate and accommodate scientific ideas, and terminology. It is recommended that teachers develop student modeling skills and that they discuss analogical models, including shared and unshared attributes, with their students. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

Constructivist learning theories emphasize the active role played by the learner in the construction of knowledge (Tobin, 1993). Each day of their lives, students interact with the natural world, observe its features, and talk to other people about experiences and ideas. Out of these accumulated experiences, students develop rudimentary explanations or generalized mental models of many phenomena including life, astronomy, light, force, and matter. These intuitive ideas or "children's science" (Duit & Treagust, 1995; Gilbert, Osborne, & Fensham, 1982) directly influence students' classroom learning, and because individual experiences are many and varied, the influence of this prior knowledge on learning varies from student to student. In the main, however, alternative student conceptions have been well documented (Driver,

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Squires, Rushworth, & Wood-Robinson, 1994; Pfundt & Duit, 1994). Nevertheless, student descriptions of scientific phenomena are often exemplified by their individuality and unique construction and this is demonstrated by this offering from a student in a pretest at the beginning of Grade 11:

> Gina: I think an atom has a dense "structure" in the middle like a ball made up of tiny particles that are neutrons and protons—like a rasp[b]erry or blackberry. This inside structure is surrounded by electrons—tiny little particles much smaller than the nuclear components. They're not solid so they don't have a shape. It is sort of like a rasp[b]erry surrounded by hula hoops or like a plum in that there is a dense matter in the middle which is surrounded by much less dense area where the electrons are.
>
> Question: How is the atom unlike the object you have chosen?
>
> Gina: The area where the electrons is not like the flesh of the fruit. They are tiny whirling things that move around like the hula hoops. The stone in the fruit is solid whereas the nucleus is not, it is made up of smaller particles grouped together.

STUDYING STUDENT MENTAL MODELS OF ATOMS AND MOLECULES

Mental Models

Vosniadou (1994) explained that mental models "refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning" (p. 48). Throughout her study, Vosniadou called her interpretations of students' conceptions of the Earth, force, and heat, mental models. Norman (1983) pointed out that mental models are intrinsic descriptions of objects and ideas that are unique to the knower and arise and evolve "through interaction with a target system" (p. 7). Mental models need not be technically accurate, but they must be functional. Norman went on to warn that "people may state (and actually believe) that they believe one thing but act in quite a different manner" (p. 11) and for this reason it should be remembered that all data and interpretations pertaining to student mental models are just that, interpretations. Several contributors in Gentner and Stevens (1983) used the construct "mental model" to describe student understanding and this term was also used throughout by Vosniadou (1994). In this article, we have consistently used the term "mental models," to describe our interpretations of individual student's conceptions of atoms and molecules.

This descriptive study of students' mental models of atoms and molecules is an investigation of how 48 students from Grades 8–10 perceived atoms and molecules. Various students described atoms as being like a ball, a solar system, a plum, and even as a structure that is able to divide and reproduce like a cell. Teacher-initiated metaphors such as "electron clouds" and "electron shells," however, appeared to conjure, in the minds of students, quite different models from those intended by the teacher. Novice students (and some not so inexperienced) held a view of an electron cloud as a matrix within which the electrons were embedded like the water droplets in a cloud. This model is very similar to the conception that matter is continuous with atoms embedded in the parent substance (Renstrom, Andersson, & Marton, 1990).

It appears that many students do not interpret teacher metaphors and analogies in the intended manner. Rather, they transfer attributes from the teachers' analog to the target (atoms and molecules) in a literal and undifferentiated sense. The need for care when using analogies to avoid the transference of unshared attributes to the target has been highlighted by Glynn (1991), Harrison and Treagust (1993), and reviewed by Duit (1991).

Research into student conceptions of the particulate nature of matter has been conducted by Andersson (1990); Lee, Eichinger, Anderson, Berkheimer and Blakeslee (1993); Nussbaum and Novick (1982); and Scott (1992). These studies considered several intuitive student views: for instance, that matter is continuous without spaces between particles; that matter is not always conserved during chemical reactions; and that atomic and molecular properties resemble the macroscopic properties of the substance. Sandomir, Stahl, and Verdi (1993) have probed student conceptions of the metaphor "an atom is an electron cloud" and "an atom is an electron shell" and showed that, frequently, students are unable to reliably identify where the metaphor (or analogy) breaks down.

The study reported herein extends the research described above by examining the reasoning behind certain views of atoms and molecules held by students and investigates *how* students' mental models may assist or hamper further instruction in chemistry. The study also explores the variety of student models of atomic structure. These data provide a baseline for a later, in-depth study of how student conceptions of models of atoms and molecules change during instruction (Harrison & Treagust, 1995).

MODELS AS REPRESENTATIONS OF REALITY

Modeling in Chemistry

> What "truth" can we show with models of atoms and molecules? This question should never be far from us as we use models to help explain and predict chemical changes. A model cannot represent fully the thing modelled, and it may even mislead us if we imagine that the thing modelled must behave as predicted with the model. (Keenan, Kleinfelter, & Wood, 1980, p. 188)

The use of the term "model" is a source of considerable semantic variation for science students and practitioners. What do we really mean when we say that two white balls separated by a black ball and interconnected by some springs is a useful model for carbon dioxide? What do we mean when we say that Le Chatelier's principle is a good model (or algorithm) for solving equilibrium problems? Or again, what do we mean when we use colliding balls in a kinetic theory apparatus to model ideal gas behavior?

The meanings for the term *model* are almost as varied as the array of models used in chemistry! The following seven categories constitute a composite definition that may be tendered for the concept, model, and is applicable to most science learning (Black, 1962; Gilbert, 1993; Gilbert & Osborne, 1980).

Scale models of a building are used for planning purposes, scale models of a car guide advertisers, and scale models of a boat are used for tank testing. While these models faithfully resemble the external proportions of the object modeled, they usually bear little or no resemblance to the object's internal structure.

Analogical models have one or more of the target's attributes represented in the analog's concrete structure. Examples are ball-and-stick and space-filling molecular models in chemistry and anatomical models in biology, for example, a plastic human torso or model heart. Analogical models are constructed to reflect point-by-point correspondences between the analog and the target for the set of attributes that the model is designed to elucidate. The shared attributes, however, are intended more to reflect abstract patterns and relationships than proportions of magnitude.

Mathematical models consist of physical properties (e.g., density), physical changes and processes (e.g., $k = PV$, $F = ma$) and mathematical functions represented in the form of an equation (e.g., $ay = bx^2 + c$). Graphs can also be used to represent equation relationships (e.g., Boyle's law, reaction enthalpy changes).

Chemical formulas (e.g., CO_2) and chemical equations model compound composition and chemical reactions, respectively. Chemical equations can represent reaction stoichiometry, thermodynamic and electron changes, reaction mechanics, and equilibrium states.

Theoretical models are used to analogically represent nonmaterial phenomena like magnetic lines of force and photons, for example. Mental models of phenomena involving these entities may also belong to this category.

A *model* or *standard* is something to be imitated. An example would be a model of a process that makes sense of an overall chemical or physical change (e.g., kinetic theory models for temperature, pressure, and phase changes).

Maps and *diagrams* represent patterns and pathways. Examples are weather maps, electrical circuit diagrams, chemical synthesis flow diagrams, metabolic pathways, and nervous system and circulatory patterns.

Development of Models through History

The concept that matter was composed of atoms began almost 2500 years ago with the Greek philosophers Democritus (B.C. 460) and Leucippus. Modern atomic theory, however, grew out of the work of John Dalton (1766–1844) and with the move from alchemy to a more systematic study of the elements and their behavior (e.g., Lavoisier, Priestley, and Davy), chemists were challenged to describe atoms and molecules. Early theories depicted atoms as spheres or balls; this idea was refined with Thomson's discovery of the electron and the emergence of his "plum-pudding" model of the atom. The discovery by Rutherford that atoms are almost all space and have a dense nucleus led to the "solar system" model. This model, however, was quickly refined as the Bohr atom, and quantum mechanics generated an ever more abstract atomic model that required sophisticated mathematics for its description (after Planck, de Broglie, Schrödinger, and Heisenberg).

Mathematicians such as Kline (1985) argue that, despite the desire to produce mental or analogical models of abstract objects and processes, the belief that we can do so is a myth. This is because when dealing with space, mass, light, and gravity, the notion that there is an exact correspondence between mathematical descriptions and physical models is a retrograde step. He comments: "what is most relevant for us to see is that our models of atomic structure are not physical" correspondences with real objects like atoms (Kline, 1985, p. 196). This is the basis of the dilemma: theoretical scientists enjoy startling the world with their discoveries and have a genuine desire to disseminate new ideas which often improve our world. However, while scientists achieve many of these advances through mathematical pathways, the teacher, who is the second last link in the education chain, is pressed to employ imperfect models and analogies that the theoretician deplores. Ironically, writers such as Kline use a wide range of analogies to transmit their own ideas to the average reader while criticizing models and analogies as "impure."

Even a cursory glance at modern science textbooks reveals that they contain many analogies and analogical models. Probably nowhere is this more obvious than in chemistry textbooks (Thiele & Treagust, 1994a), chemistry laboratories, and chemistry teacher explanations (Thiele & Treagust, 1994b). To introduce nonobservable entities like atoms and molecules to students, teachers and textbook writers are constrained to introduce analogies, analogical models, and representational models like chemical formulas and chemical equations. Paralleling science's evolution of atomic models, it often happens that, over the 5 years of secondary chemistry instruction in Australia, teachers employ the historical succession of models in a spiral curriculum.

Analogical Models of Molecules Used in Chemistry Instruction

Keenan et al. (1980) described four common molecular model types encountered in secondary chemistry classrooms. Not only do these authors discuss modeling with their readers, they also describe the shared and unshared attributes existent between each analog (the model) and its target (the molecule). An example of each model is shown in Figure 1.

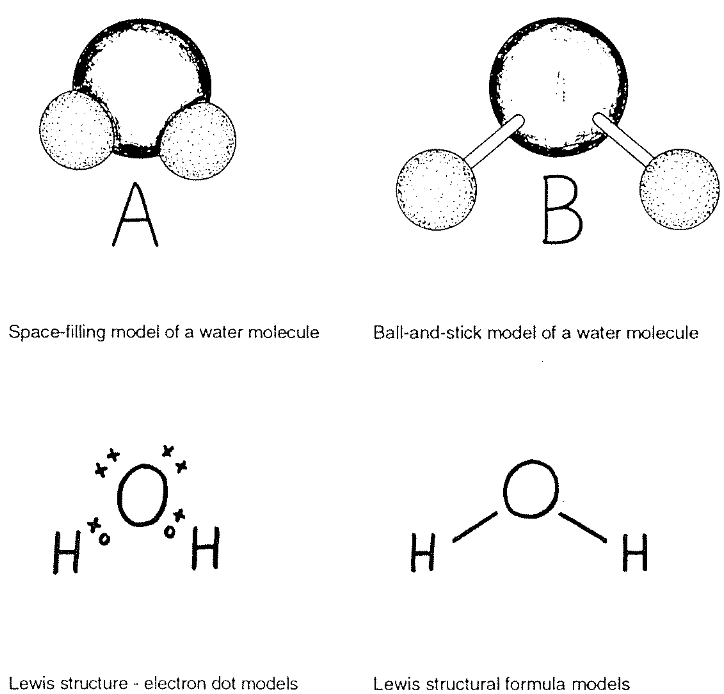

Figure 1. Four types of molecular models commonly used in secondary chemistry classrooms.

Scale models or space-filling models roughly represent van der Waals and covalent radii. Bond angles and relative atomic sizes are depicted with adequate accuracy. The overall architecture of the molecule is well represented. This model's weakness lies in its inability to show bond numbers and bond type.

Ball-and-stick models provide simple three-dimensional representations and the number of bonds to each atom is correctly shown, and often the models show the correct bond angle. These models are easy to make from proprietary sets and the double and triple bonds do show their nonrotatable nature in contrast to the fully rotatable single bond. Ball-and-stick models are similarly excellent for demonstrating isomerism. On the negative side, these models give an idea of "openness" and, as most balls are the same size, they imply that all atoms are the same size (which they are not). Double and triple bonds are represented by bent plastic or springs so that the single and multiple bonds each appear to be structurally identical (which they are not). Furthermore, ball-and-stick models cannot satisfactorily depict a benzene ring.

Lewis structures (models of molecules) are two-dimensional diagrams showing all the valence shell electrons for the interacting atoms, and they obey the octet rule for second row elements and the duet rule for hydrogen. Their advantage lies in ease of use and ability to show all bonding electrons as well as allowing the student to "work out" a satisfactory structure and deduce, in many cases, the molecule's shape. These diagrams, however, are flawed in that they are only two-dimensional and do not show bond type and fail to work in more complex cases.

Structural formula models are derivations of Lewis structures with the addition of splayed and dotted bonds to depict in-front-of-the-plane and behind-the-plane orientations, respectively. These structures allow three-dimensional diagrams (e.g., tetrahedra) to be drawn on paper, but cannot accurately show the bond angles nor can they distinguish bond type. Students need time to develop the visualization skills needed to read these diagrams but they are quick and easy to draw on paper.

Student Modeling Ability

Because chemistry deals with atoms, molecules, and ions that are unimaginably minute, changes at the particle level are only explainable by theories that utilize a plethora of models. Understandably, atomic theory depends more than any other topic in chemistry on a variety of models to explain particulate behavior. Many students however, find the diversity of models used to represent specific phenomena both challenging and confusing. This problem is particularly severe for young students and for those students whose abstract reasoning is weak. In investigating the modeling capabilities of students, Grosslight, Unger, Jay, and Smith (1991) found that students could be assigned to one of three arbitrary levels.

Essentially, Grosslight et al. (1991) synthesized "three general levels of thinking about models reflecting three different epistemological views about models and their use in science" (p. 817). A level 1 modeler thinks of models as "toys or simple copies of reality" and accepts that some real attributes are missing from the model simply because the modeler wanted it that way. Many students at this level imagine that there is a general 1 : 1 correspondence between the model and reality. Level 2 modelers appreciate "that there is a specific, explicit purpose that mediates the way the model is constructed" and are "aware that the modeler makes conscious choices about how to achieve the purpose" (p. 817). At level 2 it is understood that the model does not have to correspond with reality; nevertheless, students at this level still focus on the model and the reality it portrays rather than the ideas it represents. Level 3 modelers recognize that the model serves the development and testing of ideas, not the depiction of reality. Students at this level would construct and manipulate diverse multiple models without being perturbed by their differences. The model serves the modeler, not the modeler the model and reality.

METHOD

Subjects and Context

Forty-eight students, selected from Grades 8, 9, and 10 at three large senior high schools (Grades 8–12) in Western Australia, were the subjects for this study. None of the schools had a policy to restrict access to any student, and students in Grades 8–10 are generally in nonstreamed classes. Two of the schools were government senior high schools (one metropolitan, the other in a large country town) and the third was an exclusive metropolitan girls school. For all except the Grade 8s in the country school, approximately half of the students in each class were unavailable due to excursions or being involved in other end-of-academic-year school functions. Student willingness was the principal selection criterion. Given these self-selection criteria, it is likely that the students who were engaged in this study were representative of all but the weakest students in these grade levels.

The distribution of subjects interviewed comprised: 13 students from Grade 8; 18 from Grade 9; and 17 from Grade 10. Each student had studied at least one chemistry unit per year through Grades 8–10 in the science curriculum and had encountered models of atoms and molecules during this teaching. As the interviews were conducted during the last month of the second semester in November, students from the three grades had received 1, 2, or 3 years of secondary science instruction, respectively.

The Interview Protocol

The study itself used a semistructured focused interview protocol of, on average, 20 minutes duration to probe student conceptions. In commencing each interview, the student was given a piece of aluminum foil and block of iron and asked "What do you think these are made of?" In every interview, the student stated that the iron and the aluminum was either made of atoms or particles. When the students did not mention atoms after four or five probing questions, they were prompted with the term "atom." Next, every student was asked to think about his or her mental model of an atom and asked to draw this on a sheet of paper and describe the drawing. As most students drew or mentioned a ball or sphere, each student was given a 5-cm-diameter polystyrene ball and a 5-cm-diameter pompom (with a hard center) and asked if either of these models shared any similarities with their diagram and description. The students were then shown the sheet containing six diagrams of "some of the ways atoms have been described" (Fig. 2, diagrams 1–6). These diagrams were drawn by the authors and were based on diagrams found in textbooks used in Australian schools or drawn by teachers. The freehand quality of diagrams 4 and 5 may have appeared less attractive to some students, however, the diffuse nature of these two diagrams was intended. Each student was asked to circle the diagram which best fitted his or her mental model of an atom and was then asked for the second and third best fit diagram (if possible) and to identify diagrams they did not like. Often, during this discussion, the student introduced the terms nucleus, electron shell, electron cloud, electron movement, protons, and neutrons. Each of these items was discussed at that point or, if not introduced by the student, the interviewer cued and asked each student about electron clouds and electron shells.

The discussion then moved to molecules and each student was given a space-filling and a ball-and-stick molecular model for H_2O (Fig. 1). Each student's preference for each of these models was explored and reasons sought for their choice. Finally, most students were asked to describe how far they thought the electron cloud extended out from the nucleus of the atom, where it started, and where it finished. This estimation was based on the 5-cm-diameter polystyrene ball representing the nucleus of an atom. During each interview, students either volunteered or were asked whether they thought all substances contained atoms (or not) and whether they thought scientists have actually seen atoms (or not).

Each interview was audiotaped and transcribed verbatim. The transcripts were combined with the students' drawings and formed the data corpus for analysis.

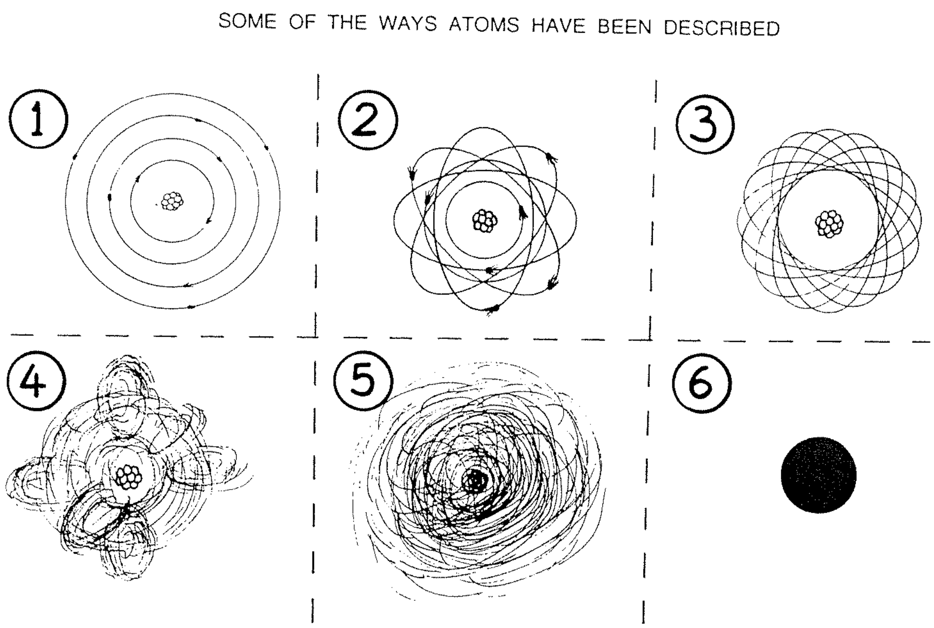

Figure 2. The set of six diagrams of atomic models shown to the students.

Analysis of Student Interviews

Initially, the student interviews were analysed and described in Harrison and Treagust (1994, 1995). This, and subsequent analyses of the data corpus, identified three categories under which the student responses could be analyzed and the results classified. In all, each interview was read three times by the first author. The first reading examined the students' conceptions of atomic shape, size, and choice (as detailed in Fig. 2) as well as determining their familiarity with electron shells and electron clouds. The second reading provided all of the other data tallies except for each student's Modeling Ability which, in most cases, was ascertained by a third reading of the transcripts.

First, the students' choices from the set of six diagrams in Figure 2 yielded two distinct criteria: students' preferred atomic models (subdivided into best, better, and good); and models disliked by the students. Only the totals for each criterion's heading were computed and these are recorded in Table 1.

Second, student responses were organized under the ten criteria of: Atoms, Size of Atoms, Composition of Matter, Living Atoms, Shape of Atoms, Texture of Atoms, Electron Shells, Electron Clouds, Molecular Models, and Modeling Ability. These data are listed in Table 2. For two criteria (Shape of Atoms and Molecular Models) the data totals exceed 48 because some students chose both models. For other criteria, the student's lack of knowledge, time shortage, or the interview's direction meant that a particular question was not answered or was not asked. In these instances, there are tallies for "Not asked, no response."

The assignment of each student as a level 1, 2, or 3 modeler deserves comment. Grosslight et al. (1993) formulated their three levels from interviews that directly discussed student ideas about models. If students were not clear modelers at the higher level, we scored them at the lower level rather than deciding upon any mixed level scores (i.e., levels 1/2 or 2/3). In this study, the interviews focused on atoms and molecules and the conclusions about students' modeling abilities were derived from students' comments about the various models rather than on modeling *per se*.

Students often seek cues and endeavor to provide responses they think will please their teacher or the interviewer. It was felt that this less direct approach may possess high validity as it avoids asking interviewees direct questions.

Third, students' models of the size of the atom's electron cloud were analyzed and evaluated. Students were shown a 5-cm-diameter polystyrene ball and asked: "If the atom's nucleus was as large as this ball, at what distance from the nucleus do you think the electron cloud starts? . . . stops?" Variability in the individual distance ranges defied simple classification. Each student's distance range is therefore depicted as a bar in Figure 3. It was necessary to employ a logarithmic vertical scale to accommodate the breadth of student estimates. The individual estimates were ranked by size.

MENTAL MODELS HELD BY SECONDARY SCHOOL CHEMISTRY STUDENTS

Sylvia: Well an atom is made up of protons and neutrons and electrons and has a nucleus and has an electron cloud around it which has a certain amount of electrons depending on what sort of atom it is, um, the nucleus contains the protons and the neutrons and around it are the electrons and each of the different ones are positive and negative or neutral.

[Grade 10 student]

Int: Do you have any ideas about the shape of an atom?

Jill: Are they round, aren't they sort of rounded and they're really, really small and they are generally in groups, they are sort of joined together in groups . . . a very, very small ball.

. . . Um, well, aren't atoms sort of soft on the outside and they've got a hard centre and so it'd be more like [the pompom model] but they're . . . round and they're only hard in the middle, aren't they? I think.

Int: Can you draw an atom for me? Tell me what you're doing.

Jill: . . . [drawing] . . . . . . Well that's the outside, and that's the middle, like the outside's the electron cloud, that's right, and the middle's like the center and it's harder than the outside and it's got two other things in it . . . some other things and they've got things inside of it.

Int: You said that center is hard?

Jill: Well not hard, but harder than the outside, the outsides are really soft.

[Grade 8 student]

Students' Preferred Models of Atoms

The distribution of student responses to the six diagrams representing atoms in Figure 2 is given in Table 1. Each student preferred at least one diagram and some chose two or three diagrams as being acceptable and all found at least one diagram they disliked. Some students rejected two or more diagrams.

Thirty-one students chose the orbits model (number 2, Fig. 2) as their first or second choice. This diagram probably best represents the popular conception of an atom as used on television and in the print media. Twenty-four students rejected the orbitals model (number 4, Fig. 2) compared to five who approved of it at any

TABLE 1
Frequency of Student Preferences for Analogical Models Presented in Figure 2 ($n = 48$)

	Classification			
	Best	Better	Good	Dislike
1. Solar system model	5	12	4	3
2. Orbits model	22	9	3	1
3. Multiple orbits model	7	11	7	1
4. Orbitals model	3	1	1	24
5. Electron cloud model	8	7	1	8
6. Ball model	3	3	2	11
Totals	48	43	18	48

level; being Grade 8–10 students, the orbitals model was most likely unacceptable due to its unfamiliarity. The number of students who disliked the electron cloud model (number 5, Fig. 2) equaled the number who awarded this model their "best" choice. It was notable that twice as many students approved of this model as rejected it (16 best + better + good, 8 dislike). Overall, approximately the same number of students chose the solar system model as those who chose the electron cloud model (21 to 16, respectively); however, more than twice as many students disliked the electron cloud model than disliked the solar system model! Students who are less initiated into scientific representations may favor distinct, concrete models because such models resemble their everyday world objects. That is, they visualize science concepts as possessing matter rather than process attributes (Chi, Slotta, & de Leeuw, 1994). The solar system and the orbits model showed each subatomic particle as a separate entity *and* gave the electron paths a material flavor by drawing them as complete circles or ellipses. On the other hand, the electron cloud model was more diffuse and thus was less material from the students' viewpoint. The level of student approval for the electron cloud model may have been artificially high. Some students may have chosen this representation because of the emphasis that teachers gave to electron clouds. Support for this notion is derived from the observation that 50% of all students and nearly 60% of those who responded had heard of electron clouds (see Table 2).

Student Descriptions of Their Mental Models of Atoms

The data collected from the students during the interviews produced some predictable and some unexpected responses. The notable unexpected responses were the assertion by a majority of the respondents that atoms are visible under a powerful microscope and the smaller, but significant, number of students who believed that atoms were alive and could reproduce. Each of the ten categories listed in Table 2 is discussed.

Atoms

Atoms were not introduced by all the students at the start of the interview when the question "what do you think the aluminum foil and the iron block are made of?" was asked. However, when cued, each of these students stated that he/she was familiar with the concept "atom." While almost one third of the students needed to be cued, 12 of the 15 students in this group were from Grade 8 with only one Grade 9 and two Grade 10 students needing a reminder. It is suggested that the Grade 8 students' limited experience with atoms accounts for this observation.

Size of Atoms

This criterion produced an unexpected finding. Although most students think that atoms are like "a very, very small ball, incredibly small" [Jenny, Grade 10], many

TABLE 2
Frequency of Student Responses in 10 Conceptual Categories Concerning Atomic and Molecular Attributes ($n = 48$)

Criterion	Attribute	Frequency	Percentage
Atoms	Student volunteered the term atoms in interview	33	69%
	Student was cued with the term atoms	15	31%
Size of Atoms	Atoms are visible under a microscope	24	50%
	Atoms too small to see	15	31%
	Not asked, no response	9	19%
Composition of Matter	All substances contain atoms	34	71%
	Some substances made of other objects	7	15%
	Not asked, no response	7	15%
Living Atoms	Atoms are inanimate	38	79%
	Atoms are alive, grow and divide	10	21%
Shape of Atoms	Atoms are balls or spheres	29	55%
	Simple diagram with nucleus and electrons	17	32%
	Simple circle in a circle	7	13%
Texture of Atoms	Atoms most like a hard polystyrene sphere	26	54%
	Atoms most like a pompom with hard center	18	38%
	Not asked, no response	4	8%
Electron Shells	Aware of electron shells	13	27%
	Not aware of electron shells	29	60%
	Not asked, no response	6	13%
Electron Clouds	Aware of electron clouds	24	50%
	Not aware of electron clouds	17	35%
	Not asked, no response	7	15%
Molecular Models	Prefer space-filling models	41	76%
	Prefer ball-and-stick models	13	24%
Modeling Ability (Grosslight et al., 1990)	Level 1 modeler	28	58%
	Level 2 modeler	20	42%
	Level 3 modeler	0	0%

believed that atoms could be seen using a powerful microscope. Of the 39 students who commented on this item, 62% asserted that scientists could see or have seen atoms. Lee et al. (1993) found that Grade 6 students held similar unorthodox conceptions of the size of molecules. Even after the treatment group had been taught using revised instructional materials that addressed this alternative conception, students "still believed that they could see molecules with microscopes or 'magnifying lenses'" (p. 257).

If students think that scientists have seen atoms, then their attitude toward the diagrams generated by experts and the diagrams they see in textbooks, in the classroom, and on TV, and so forth, is such that they may well view these diagrams as "the real thing." But there is an inherent problem for students with this perception: the diagrams are many and varied as indicated by Figure 2. If they believe that scientists have seen atoms, then which diagram (if any) is the real thing? It is worth noting that not every student expressed a second preference when examining Figure 2 (89% did) and only 38% made a third choice (only one student rated all six diagrams). Put another way, five students chose a single model and 30 chose two models (and 12 of these students chose diagrams 2 and 3 which are quite similar).

Whenever any of these models are used during instruction, it appears essential that teachers explain that each diagram is only an analogical model and that scientists have not seen individual atoms. Students need guidance to help them understand that each model contains some valid features along with many invalid features and therefore, the unshared attributes should be identified for the students by the teacher.

Composition of Matter

The replies to the question "Are all substances made up of atoms?" showed that 83% of the students who responded to this question acknowledged that all matter is composed of atoms. Five of the seven students who stated that materials were made of objects other than atoms asserted elsewhere in the interview that atoms are alive or are like cells. It is likely that the other objects which also make up matter in their cases were cells. Three of these seven students made unambiguous comments indicating that nonliving things are composed of atoms but living things are made of plant and animal cells. This confusion may be linked to the next criterion.

Living Atoms

This assertion was made by 10 (21%) of the 48 students interviewed. These students described atoms as "living," or "like cells," as behaving purposefully and, in two cases, able to reproduce! Nell, a Grade 9 student, provided these remarks:

> Int: What's this center thing [diagram 2]?
>
> Nell: Nucleus.
>
> Int: What are these little things around here [pointing to electrons]?
>
> Nell: They sort of like, um, shield . . . for the nucleus.

> Int: What do you understand by a shield?
>
> Nell: Like protects it, and it like helps it like, so once it is coming into two, break up, it's got something to shield them both.
>
> Int: What breaks into two?
>
> Nell: The nucleus
>
> Int: Why would it break into two?
>
> Nell: Oh, I dunno, like helps it to grow, in there . . .
>
> Int: So these can grow?
>
> Nell: Yea, like, not make the metal bigger or something, just like they break up so there's more of them.
>
> Int: And what do these little ones do when they've broken up?
>
> Nell: They grow and they break into more.

Other students appeared to have confused the nucleus of the atom with the nucleus of a cell and one Grade 8 student, Bob, actually drew a cell for an atom:

> Int: Do you have a picture in your mind of what an atom might look like?
>
> Bob: . . . [drawing] . . . I always had the idea that an atom was like a cell of some sort, but we never really, we worked on it for about a week in class, and [it is] made up of extremely small cells . . . Ah, ecto . . . plasm . . . I think it is and a cell membrane . . . around this . . . and everything is made up of billions of tiny atoms.

Later, Bob asserted that, for an atom, you could "compress it, stretch it, and you can always put it back to its original shape." But that was not all, on two further occasions, he returned to his atom/cell conception when discussing the six diagrams (Fig. 2). The majority of Bob's transcript indicated that he was talking about atoms but had integrated cell ideas into his mental model of atoms. Shelley, from the same Grade 8 class, made very similar comments:

> Int: What do you think an atom looks like?
>
> Shelley: Well, you see them under a microscope, so I suppose it'd look like cells or something . . .
>
> Shelley: [later] To split it easier, that's all, about splitting atoms.

Another student called the atom's nucleus its control center, saying that the nucleus controlled the atom's activities. It is probably significant that all but two of the students who exhibited this alternative conception were taught the chemistry unit by a specialist biology teacher. A student from another school, however, also used this living or cell-like idea even though he was taught by a physical science specialist. It appears that teachers need to be vigilant in differentiating between the nucleus of a cell and its functions and the nucleus of an atom.

This biological influence also was evident when discussing electron shells. Where students indicated some familiarity with the electron shell idea, they were asked "What do you think of when we mention the term shell?" All the students who responded to this question saw a shell as acting as a form of protection and, where examples were used, they were snail shells, beach shells, clam shells, and egg shells. A typical response from Kylie in Grade 9 went like this:

> Kylie: That's the, . . . right out there is the shell, and then . . . that's [indicating] the nucleus. . . .
>
> Int: Shell of what?
>
> Kylie: The shell of the atom.
>
> Int: What do you think the shell, when I say shell, what do you think of?
>
> Kylie: Apart from an egg shell, something, er, like a hard coating around the outside.

It thus seems inappropriate to use the "electron shell" metaphor without explicitly defining the intended meaning, namely that of a level or position. The students interviewed were drawn from 11 different classes in three schools and, although 27% of the students stated that they were familiar with the notion of electron shells, not one student used the idea in the intended chemical sense.

Shape of Atoms

Student drawings, and comments made during the interview, provided these data; the total exceeds 48 because several students chose two models. Students were deemed to hold a ball-like mental image if they drew a simple circle or described an atom as a ball, a sphere, or said that the atom was round and solid. It is intriguing that 55% of these students expressed the opinion that an atom was like a ball or sphere yet chose spatial diagrams from Figure 2 and showed little preference for the ball model depicted in diagram number 6. This uncritical acceptance of contrasting models suggests that understanding in this domain is quite superficial.

Texture of Atoms

Andersson's (1990) review and Lee et al.'s (1993) study showed that students believe that the properties of atoms and molecules resemble the substance's macroscopic properties. For example, Andersson found that students believed that particles were colored and this same belief also was found in this student sample. Students told Lee et al. (1993) that water "molecules are frozen in ice, because they are solid together" (p. 261). To ascertain whether this also applied to texture, students examined the hard polystyrene ball and the soft pompom with a hard center which they were shown as models of atoms. Of the 44 students who expressed a preference, 54% believed atoms were hard and 38% believed they would be soft. One student chose both, stating that the polystyrene ball represented the hard nucleus, while the fluffy pompom represented the electrons [Natalie, Grade 8]. Several students believed that the polystyrene ball was too regular for an atom, that the slightly irregular surface of the pompom better represented their image of the electrons surrounding the nucleus.

Even though they preferred the polystyrene ball, two students stated that the balls represented atoms in different phases. Melissa from Grade 9, reasoned this way:

> Int: Do you think atoms are hard or soft?
>
> Melissa: . . . they could be either.
>
> Int: Sometimes hard, sometimes soft?
>
> Melissa: Yep . . . it depends on what it's making really, whether it's a metal or a liquid.
>
> Int: So we talked about a metal, what would you say?
>
> Melissa: Probably be hard.
>
> Int: A liquid?
>
> Melissa: Probably be softer . . .

Electron Shells

Slightly more than one quarter of the students (13) admitted familiarity with electron shells. When probed by asking "When I mention 'shell,' what do you think of?" most responded with a comment about sea shells, clam shells, and egg shells. For these students a consistent image was evident in that they believed that atoms are protected by an outer shell. Chi et al.'s (1994) epistemological theory posits that, when a student assigns a phenomenon such as an atom to a Matter "tree," material features like volume and mass are attributed to that phenomenon. In this situation, students have shown that, in the main, they see atoms as concrete particles with discrete parts. It is not surprising, therefore, that they visualize electron shells in such a realistic way.

Electron Clouds

A number of the students spontaneously mentioned electron clouds during the interviews. Twenty-four students (50%) indicated some degree of familiarity with electron clouds, whereas 17 students (35%) said that they were unfamiliar with this metaphor. Seven students were not asked or did not respond.

For example, James, who was in Grade 10, introduced electron clouds early in the interview:

> James: . . . and around the nucleus is a thing called an electron cloud, and each electron spins around the nucleus and this makes the atom work, and the electrons are positively . . . no negatively charged and the neutrons are neutral . . . and the protons are positively charged.
>
> Int: You called that an electron cloud. Why do you use that term?
>
> James: Because um, . . . it has no like solid structure it's usually shaped . . . it can be in all different types of shapes . . . it's not solid.
>
> Int: What makes it into a cloud?
>
> James: The electrons.

James, and a number of other students, described electron clouds in a manner that is appropriate for Grades 8–10. However, a significant alternative conception was encountered in which other students described an electron shell as a matrix in which the electrons were embedded. Each student who demonstrated some familiarity with the electron cloud metaphor was asked "When I say cloud, what do you think of?" Most replied, "Clouds in the sky," and two students spoke of clouds of dust or clouds of smoke particles. When the "clouds in the sky" idea was pursued, several students added that the electron cloud was like a cloud in the sky and the electrons were like the droplets of water in the cloud. Further discussion indicated that these students saw the cloud as a separate entity, containing the electrons. This notion is similar to the conceptual category described by Renstrom, Andersson, and Marton (1990), in which students visualize matter (e.g., copper) as consisting of atoms embedded in a matrix of that substance (copper). For instance, Carol, in Grade 9, said:

> Int: Have you heard of the term an electron cloud?
>
> Carol: Yep, it's the stuff all the electrons are in I think.
>
> Int: What's this stuff?
>
> Carol: It's er, I think it's a kind of substance . . . holding them together or something.
>
> Int: Can you see a cloud out there?
>
> Carol: Yep, lots of them.
>
> Int: Ok, is that like what's being referred to when we say electron cloud?
>
> Carol: No, I don't think so, I think it's a cloud, tends to be more used to say that they're, the electrons, are all held together, like that's what they all are in.

Based on these data, as with the shell metaphor, the electron cloud metaphor (or analogy) needs to be explicitly defined before it is used with or by students. These metaphoric terms have many everyday meanings and it is therefore recommended that teachers qualify the sense in which they are transferring attributes from the analog to the atom. Gilbert, Osborne, and Fensham (1982) and Sutton (1992, 1993) have shown that semantic differences between the students' and the teacher's meanings for commonly used terms in science are a source of alternative conceptions.

Molecular Models

Following the discussion of atomic structure, students were shown a space-filling (A) and a ball-and-stick (B) molecular model for water and asked to select the model they felt better represented a molecule of water (Fig. 1). This choice was simpler than in Figure 2 and there was a strong preference for the space-filling molecular model. Forty-one students (76%) preferred the space-filling model, whereas only 13 students (26%) favored the ball-and-stick model. The total exceeds 48 because several students expressed equal preference for both models.

Where students stated a reason for their choice it was almost always of the form used by Steve from Grade 9:

> Int: Which of these two models is the better for you—A [space-filling] or B [ball-and-stick]?
>
> Steve: A [why?] because they don't have spaces between them, they're all joined together.

Neil from Grade 10 put it this way:

> Neil: That one, A [why?] well when they're a molecule, they're joined together, they share the electrons so that, to me, B, is not really joined together, it's more separated in B, these ones are separated and doesn't look together.
>
> Int: The sticks represent bonds . . . ?
>
> Neil: It's not as convincing . . . A's more convincing than B.

The strength of the student views suggests that the teaching approach of drawing structural diagrams of molecules on the blackboard is not satisfactory for students of this age. Of the 13 students who preferred the ball-and-stick models, not one student gave a convincing explanation of the model or strongly defended that representation. In contrast, more than 25% of the other group of students spoke strongly in favor of the space-filling model.

Modeling Ability

When the transcripts were reviewed to classify students into Grosslight et al.'s (1991) modeling levels, a number of students were found to be transitional between levels. This was particularly evident when deciding between levels 1 and 2. The results indicate that 28 students were level 1 modelers and 20 were wholly or mostly level 2. Even though one student was a mixed level 2/3, this student was classified as a level 2 modeler. When the descriptors of Grosslight et al.'s classification are recalled, many of the difficulties that students had with atomic and molecular models become more understandable.

The majority of the 48 students were at or retained vestiges of level 1. At this level, students believe that there is a strong correlation between the model's structure and reality (in this case the atom). That 20 students (42%) were at or close to level 2 is encouraging. This demonstrates that a significant proportion of these students were beginning to differentiate between the model and reality. This intellectual growth should be accompanied by an increasing ability to recognize that overtly different models merely represent different aspects of the same phenomenon. If developed, this potential should allow these students to develop more scientifically acceptable mental models of scientific phenomena. The recommendation that teachers teach modeling skills should be extended to say that modeling instruction should be maintained throughout the science curriculum.

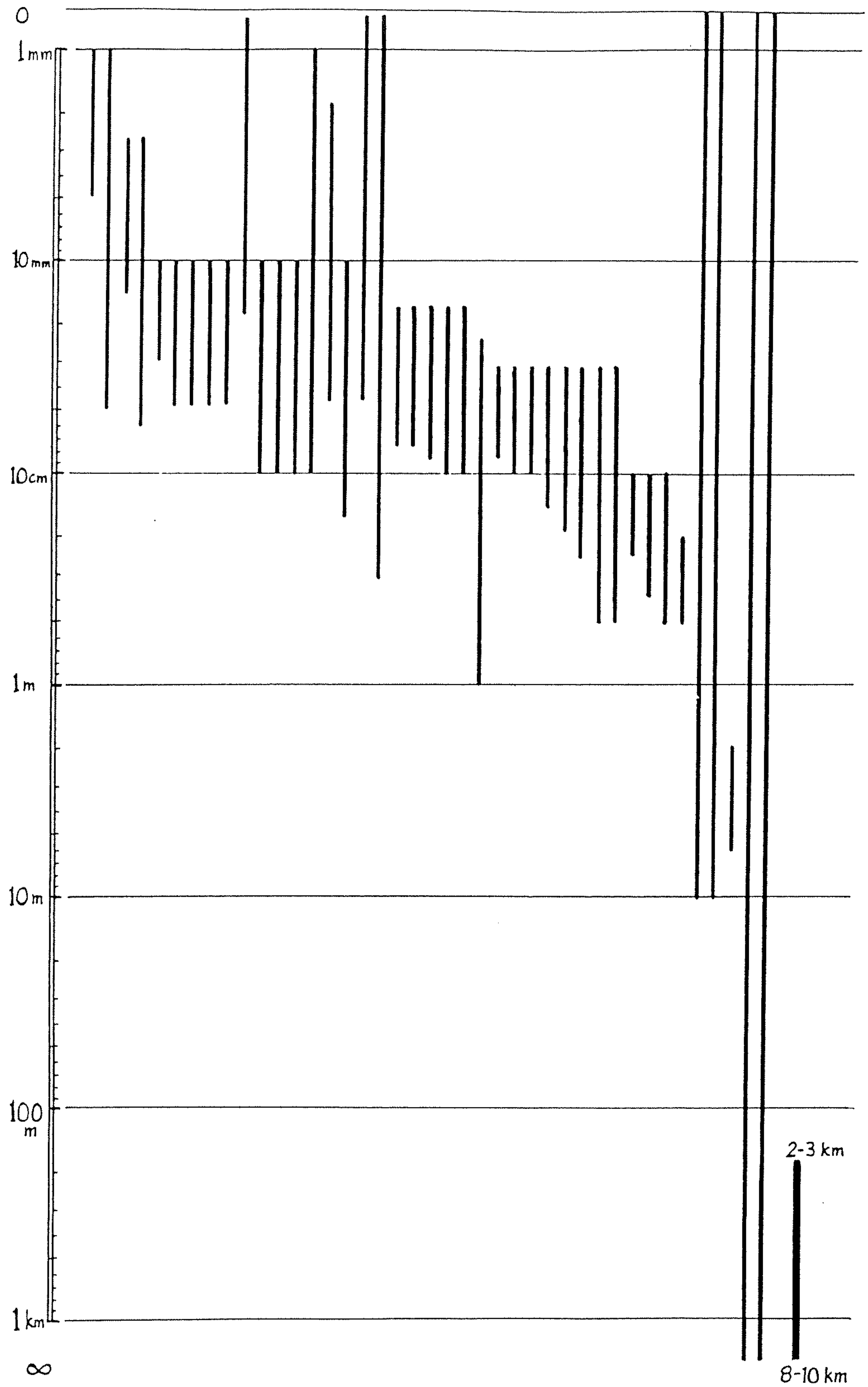

Figure 3. Distribution of student estimates of the size of an electron cloud. Vertical scale is logarithmic.

Student's Mental Models of the Size of an Electron Cloud

Forty-two students expressed an opinion about the relative size of an atom's electron cloud. Remembering that these distances were relative to a nucleus that was 5 cm in diameter, 33 students thought that the electrons commenced around 2–10 mm from the nucleus through to an outer limit of about 50 cm. For a hydrogen atom, the ratio of nuclear diameter to atomic diameter is approximately $1:10^5$. For a nucleus 5 cm in diameter, the electrons should extend to about 5000 m. Only one student provided a realistic estimate; he said that the electrons would start "several kilometers away" and would extend "to about three times that distance." Two more students described the electron cloud as sufficiently large but erred by stating that the electrons almost touched the nucleus. Three other students believed that the electrons touched the nucleus.

The tight, compact atom described by most of these responses correlates well with the 29 students who asserted that the atom was "like a ball." Harrison and Treagust (1995) found that Grade 11 chemistry students consistently drew atoms with large nuclei and close electron orbits. Even though the competent Grade 11 students stated that the atom was mostly space, they did not convey this image in their diagrams. Both data sets (Grades 8–10 and Grade 11) indicate that the majority of students have an image of an atom that does not take into account spatial dimensions. It must be pointed out that these findings are not surprising and are consistent with textbook models that do not show the proper scale.

Concurrent Student Mental Models

It was interesting to find that students do not always reveal what they really think in tests and examinations. Consider the comment from Carol, a Grade 9 student:

> Int: Why do you like diagram 1 [planetary model]?
>
> Carol: Cause, I see it on the, when the teacher represents atoms, you know, the electron configuration kind of thing, that's the usual way she pictures it, so that's the main kind of image that comes into my mind. If we've got a test or something, that's the easiest way for me to remember what it's like.
>
> Int: You also said you liked diagram number 5 [hazy electron cloud model]. Why?
>
> Carol: Well, um, I think it's like the electrons would be in an atom. It wouldn't be that easy to remember it for a test or anything, but that's what I think that's what they would be like.
>
> Int: Are you telling me that 1 is the best and then 5 is better, it sounds like, correct me if I'm wrong, it sounds like you're saying 5's more real but it's not good for tests?
>
> Carol: Yes. . . . That's cause, um, I don't think electrons would be so like that [diagram 1], not totally . . . [symmetrical?] yea. Yea, . . . I couldn't think of the word [that's a reasonable word?] yea . . . and this one's [5] a bit more random, yea cause I know that you, they're supposed to be um, have different spaces or something for each electron, like there's a nucleus and it [the electron] goes like that and comes out and the next one, um, but I still think that it'll still be more like that [diagram 5?] yea.

Carol's response could signal the beginning of a tolerance for multiple models; then again, it may simply be her way of reconciling disparate concepts. Indeed, it is well-recognized that students are adept at tolerating the teacher's concept for the duration of the instruction while conserving their personal conception (Posner, Strike, Hewson, & Gertzog, 1982; Scott, 1992).

INTERPRETATIONS AND RECOMMENDATIONS

Sources of Student's Alternative Conceptions

Recent research into student conceptual frameworks has suggested an alternate source for student conceptions. Strike and Posner (1992) and Vosniadou (1994) propose that many alternative conceptions are actually generated during learning in the classroom as a product of the interaction between the students' preconceptions and teacher-initiated instruction. Rather than students bringing well-formulated theories to instruction, Strike and Posner assert that, instead, students possess simple explanations or models of natural phenomena. While students' initial conceptions may not be well-formulated and articulated, these models and simple explanations are nevertheless related to the students' conceptual ecology from which they emerged. Vosniadou (1994) calls these principles that organize student knowledge "naive framework theories" and asserts that these principles are grounded in ontological and epistemological presuppositions.

Thus, when rudimentary student ideas interact with teacher demonstrations; scientific language, laws, and theories; and the students' own experiences, students will try to reconcile their mental models (often referred to as conceptions or mental models by many investigators) and ideas with the accepted scientific concepts. The outcome of this reconciliation can result in the science concept being distorted into an alternative conception. Hewson (1981, 1982) reasoned that, when a student's prior conception is challenged by a scientific conception, and both conceptions achieve status of intelligibility and plausibility, the student will attempt to reconcile the competing conceptions. Hewson called this "conceptual capture." Now if the competing conceptions are in fact incompatible, and the student fails to recognize this, then an alternative conception will result. With respect to mental models, Vosniadou puts it this way: "These various mental models . . . can be explained as attempts on the part of the children to reconcile aspects of the model to which they are exposed through instruction with their initial model." (1994, pp. 62–63) Vosniadou calls these student constructions "synthetic models."

Student Mental Models of Electron "Clouds" and "Shells"

The generation of alternative conceptions during instruction may be what happened during the student interviews about atoms and molecules. The students may not have possessed clearly formulated nor well-articulated mental models of electron shells and electron clouds. They would, however, already have mental models of shells and clouds and many would have heard this "scientific" language used in teacher discourse. A simple reconciliation of the students' everyday image of a cloud with scientific concepts of atoms could have generated the "water droplets in a cloud is like electrons in an electron cloud" analogy. A similar mechanism could account for the assignment of shells to atoms as protective devices with, this time, the analogy being to snail and egg shells. If the alternative conceptions of "clouds" and "shells" were constructs of the interview, it demonstrates that students can generate alternative conceptions *in situ* from a technical discourse and, if this can happen in an interview, it could happen in a classroom. Vosniadou (1994) and Renstrom, Andersson, and Marton (1990) have demonstrated that the set of categories of alternative conceptions in a domain is reasonably stable and this was superficially evident in our interviews.

Scanning Tunneling Electron Micrograph Models

A recent scientific innovation has been the scanning tunneling electron microscope. This instrument can scan the atomic surface of a solid and generate an image of the surface atoms. Images from these instruments show individual atoms as solid, close-packed spheres. The portion of the atom delineated in these micrographs is actually a contour of electric potential for the outermost layers of the electron orbitals. Even though the electron orbitals are nearly all empty space, the computer-generated models look like solid hills and valleys in both cross-sectional and oblique views. Many of these models have now been published and constitute another potential source of alternative student conceptions. This will likely occur because uninformed students will probably interpret these models as meaning that atoms are discrete, hard balls and not mostly space.

A similar scenario was reported by de Vos (1990) where he writes that:

> In a well-known textbook on physical chemistry (Atkins, 1986) the first chapter begins as follows: "We know that atoms and molecules exist because we can see them, figures 0.1 and 0.2." The first of these figures shows a more or less symmetrical pattern of black dots of different sizes, . . . an image of a platinum needle obtained by field-ionisation spectroscopy. The second [was] obtained by X-ray diffraction . . . in a molecule of anthracene. (p. 163)

The scanning tunneling electron microscope could become another example of modeling gone wrong. The depicted models do not actually exist. The models are generated by a computer from the contours of electrical potential. This example further highlights the need for our science courses to include explicit instruction on modeling and the use of analogies (Gilbert, 1993). If students develop an understanding of the role, status, and limitations of scientific models, it is likely that they will be less inclined to see the variety of models used in textbooks and in the classroom as "reality." Grosslight et al. (1991) showed that the literature and their own studies indicated that the "model is reality" outcome is a very real possibility with younger students (e.g., Grade 7). Most of the Grade 7 students were placed in their lowest category, "level 1 understanding [where] models are thought of as either toys or simple copies of reality" (Grosslight et al., 1991, p. 817). In other words, based on the earlier section of this article, "Models As Representations of Reality," the Grade 8 students (and some of the Grades 9 and 10 students) surveyed in this study imagined that models of atoms and molecules were scale models.

Models, Metacognition, and the Nature of Science

The diversity of available atomic and molecular models provides an ideal context for metacognitive thought and discourse about the nature of science itself. Development of modeling and the systematic use of analogical models in chemistry may, in the long term, generate a more sophisticated understanding of science. These possibilities are not limited to chemistry. Multiple models are also used to explain concepts in anatomy and physiology, light, electricity, genetics, and geology. Multiple models and analogies also have the capacity to ontologically redirect science learning away from a preoccupation with matter-centered explanations toward process-driven explanations (Chi, Slotta, & de Leeuw, 1994). Some might say that all this does is intellectualize and marginalize science but there is also a powerful case for saying that modeling, analogizing, and becoming process driven makes science much more relevant to and more like everyday life.

Recommendations for Classroom Instruction

This study has identified some of the problems that arise when analogical models are used in the classroom with students who assimilate teacher and/or textbook explanations as either wholly or partly literal. The teacher's response to students' inappropriate use of analogical models could be a resolve to stop using metaphors, analogies, and models. This response would be quite inappropriate because a glance back at the meaning of the term "model" must reveal that, without analogical models, the teaching of chemistry is reduced to a mere description of macroscopic properties and changes. Analogical models are an intrinsic part of chemical understanding. In addition to atomic theory, chemical formulas, chemical equations, kinetic theory, acids and bases, and redox and reaction rates all rely on models for their explication. Rather, the better approach is to take the necessary time to develop modeling skills with the students. These skills can empower students across the curriculum because models, whether used overtly or otherwise, are encountered in mathematics and the humanities as well as in science. Student understanding probably breaks down when models are used because the students often do not recognize that the explanation or process they are using is a model and, consequently, they mistake the model for reality.

Other studies have shown that when students appreciate the strengths and the limitations of analogies and models, their understanding is enhanced (Gilbert, 1993; Harrison & Treagust, 1995; Treagust, Harrison, Venville, & Dagher, 1996). Two recommendations emerge from this study. First, some science instruction time should be devoted to the development of student modeling skills. In particular, modeling should be developed whenever students are taught about nonobservable phenomena like light, electricity, semipermeable membranes, genetics, and atomic structure and, for that matter, anywhere where there is an natural tendency for the model to be confused with reality (Harrison, 1994). This recommendation accords with and supports the findings of Grosslight et al. (1991). Second, whenever an analogy or model enters the classroom discourse, teachers should consciously ensure that the analogy is familiar and that they make the effort to identify both the shared and the unshared attributes with the students (Glynn, 1991; Harrison & Treagust, 1994; Treagust, 1993). Many of the alternative student conceptions derived from this study's interviews could have been prevented by the teacher helping the students identify where the analogical model broke down. A particular case in point was the cross-domain mapping in which several students in different classes concluded that because cells and atoms have nuclei, atoms could reproduce and that the nucleus of an atom could control the atom's activities.

CONCLUSION

This descriptive study of Grades 8–10 students' mental models of atoms and molecules demonstrated that most students of this age prefer models of atoms and molecules that depict these entities as discrete, concrete structures. This conclusion was derived from observations that students preferred an orbits model of the atom (similar to the solar system model), viewed electron shells and electron clouds as complete or semisolid structures, and preferred space-filling molecular models. Indeed, many of the students interviewed appeared to believe that there was a significant correlation between their mental image of an atom and reality. These outcomes should not be surprising given that many students of this age lack both experience with scientific modeling and the requisite intellectual maturity to successfully interpret multiple models.

This study has also illustrated the negative outcomes that arise when students are left to draw their own conclusions about analogical models. An implication from the study is the need for teachers to discuss with students their conceptions of scientific models, metaphors, and analogies. These can be direct, content-specific discussions, or they can be metacognitive reflections on the nature of science itself. Listening to students can enhance science teaching if teachers take the time to carefully consider the mental models that the students either bring to instruction or construct during instruction. It is also recommended that science curricula include explicit instruction in scientific modeling and that analogies, metaphors, and analogical models be presented in a systematic manner.

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