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# How do Teachers and Textbook Writers Model Scientific Ideas for Students?

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Abstract

Ten experienced science teachers were interviewed about their understandings of the analogical models they use to explain science to their students. The aim was to investigate the notion that teaching pedagogy is influenced by the textbooks commonly used in class. A previously developed typology of analogical models was used to classify each teacher's repertoire of models and the models found in the prescribed science textbooks. The classifications of teacher and textbook models were then compared to identify patterns, similarities and differences. In their interviews, eight of the 10 teachers volunteered that they regularly used models in their lessons. The claimed model use was least for chemistry teachers and highest for physics teachers. Textbook analysis showed that chemistry textbooks used the most models and physics textbooks the least with biology in between. Five teachers saw a need to negotiate with their students the shared and unshared attributes of teaching models and two consistently discussed the limitations of their models. Vignettes and extracts are used throughout the paper to explain how teachers and textbooks use and discuss models.

Key Words: analogical models, modelling, relational thinking, teacher reflections, textbook analysis

Science uses many models and analogies to help scientists, teachers and students make sense of the intricacies, beauty and strangeness of the natural world. Accordingly, early in their biology textbook, Kinnear and Martin (1992) explain that:

> A model is a simplified picture or representation of a complex object or process. Models can help us understand how an object is constructed or how a process occurs. A good model also helps us make predictions about how an object will behave. A model, however, is not the real thing and accepted models can change as new information becomes available. (p. 10)

This account of the heuristic, representative and changeable nature of analogical models is uncommon in school science textbooks. Kinnear and Martin also point out that models simplify complex objects and processes while Ogborn, Kress, Martins and McGillicuddy (1996) explain how exaggerated models enhance learning. On the other hand, Zook (1991) warns that students find it difficult to both generate their own models and map teacher supplied models, and Glynn (1991) and Duit (1991) insist that teachers should help their students identify the shared and unshared attributes of all models and analogies.

With these ideas in mind, consider the model used by Ian – an experienced biology teacher – to explain inheritance to his Grade-10 students:

> The [students] saw videos with actual shots of chromosomes under the microscope but it meant very little to them until they actually made their own chromosomes with poppet beads and had a set of chromosomes which they then . . . mated with the person next to them, which they thought was really exciting. They had to go through the mechanism of dividing their chromosomes so that when they combined their gametes with the person next door they ended up with somebody who had a similar complete set of chromosomes. They were able to understand how . . . you end up with an offspring that has the same complement of paired chromosomes. Then we took that concept further by marking the beads as particular genes and then with their breeding they were able to . . . determine what offspring characteristics would be . . . They started getting this idea that there was some predictability and they [were] capable of fairly high-level probability calculations. This class, allowing them time to pursue this model, arrived almost at the same end as the brighter kids but it took a lot more time. And it wouldn't have been possible without an analogy and a model that they can get their hands on because . . . the concreteness of the model actually helped them, I'm certain of it.

Ian enjoys teaching low achieving students and volunteered this story when asked how he explained difficult concepts to his classes. As he spoke, Ian was unaware that the interview was about models; but his explanation – and another about nuts-and-bolts atoms – used multiple models. It is important to sense Ian's enthusiasm for these strategies because they are his purpose built analogies and models. They work in his class because he designed and refined the activity to motivate, teach and guide his students to the desired learning outcomes.

Why was Ian so enthusiastic about his 'breeding' model? Because he felt that he was responding to his students' capabilities and interests with a familiar and relevant model. Evidence from this study, previous research, and the literature support his belief that analogies, models and metaphors are effective teaching and learning strategies. The models that suit different ages and abilities range from concrete scale models of planets and hearts though to mathematical and theoretical models of concepts like magnetic fields and equilibrium. All models share one thing, however, they are analogies that use familiar everyday objects and experiences to represent sophisticated scientific ideas, and a wealth of research supports this approach to teaching and learning in science (Curtis & Reigeluth, 1984; Dagher, 1995; Duit, 1991; Dupin & Johsua, 1989; Gentner, 1983; Gick & Holyoak, 1983; Gilbert, 1991, 1993; Glynn, 1991; Thiele & Treagust, 1994).

Consequently, the purpose of this paper is to describe and discuss teachers' views of modelling and the ways that models are used in popular science textbooks. The first research question asks: How do teachers think about the models they use to represent scientific objects and processes? A second research question asks, Are there similarities between the way textbooks represent models and the way teachers think about and teach with models? The second question is pertinent because Sanchez and Valcárcel (1999) found that when teachers choose a science textbook, 63% follow the "conceptual framework of the [textbook's] content" (p. 500). It also is known that some textbooks use idiosyncratic models (Harrison, 1994) and most textbook writers fail to map analogies and models nor do they show readers where the models break down (Glynn, 1991). Textbook models are therefore studied alongside teachers' models to explore possible links and influences.

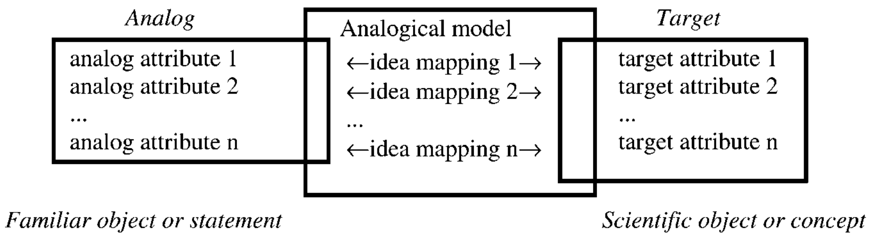


*Figure 1:* Analogical transfer of ideas from a familiar analog to a scientific target.

## Background

Analogical models are often used to research, create, test and communicate ideas (Bent, 1984; Black, 1962). Analogy is an effective way to explain unfamiliar ideas providing the explainer and the listener understand the analog in the same way. The analog is the invoked familiar object, experience or process. Partners to analogical conversations also must agree on their learning target; that is, the unfamiliar object, concept or process. Analogical explanations work when the explainer and the listener agree on the analogical mappings that exist between the analog and the target and mappings are said to be shared (positive analogy) when both parties agree that the analog is like the target in this or that way. Unshared mappings (negative analogy) are the ways in which the analog is not like the target but some mappings do not easily fit either category and are called the neutral analogy (Hesse, 1963). The shared and unshared mappings are usually called the analogy's shared and unshared attributes.

The primary concern of this paper is the analogical models (hereafter referred to as models) that are used to teach and learn school science. Analogies are usually verbal whereas models are mostly structures or pictures. A quite separate class of models are the algorithms used to explain how to do something like how to focus a microscope, plan an activity or teach in a particular way (e.g., the FAR guide; Treagust, Harrison, & Venville, 1998). Figure 1 is a useful way to describe the analogical modelling process discussed in this paper.

But are models as effective for explaining science concepts as we suppose? A number of researchers have recently tackled this question (Gilbert, 1991; Halloun, 1996; Wells, Hestenes, & Swackhamer, 1995) but there is limited theory on how teachers teach and students learn using models. John Gilbert (1993, p. 5) argues that "models are one of the main products of science, modelling is an element in scientific methodology, [and] models are a major learning and teaching tool in science education." But do science teachers share these views? Do science textbooks – particularly senior Biology, Chemistry and Physics textbooks – support this view of models and modelling? And, are models thinking tools or are they representations that can be rote learned and automatically applied by students?

There are good reasons why modelling should be a core thinking skill. First, many science phenomena are abstract (e.g., magnetic fields), nonobservable (e.g., atoms and molecules) or cannot be explained except by analogy (e.g., refraction of light).

Second, most school students are naïve realists who believe that there is a 1:1 correspondence between models and reality, models are like toys and the features included and excluded in the model are arbitrary decisions (Grosslight, Unger, Jay, & Smith, 1991). These students are usually dualists who believe that all representations are "right or wrong," "good or bad" and the trick is to second guess the teacher and rote learn the best answer (Perry, 1970). Third, many teachers depend on the textbook for planning the content and processes they teach in class (Sanchez & Valcárcel, 1999). But if textbooks do not overtly discuss modelling processes, is it surprising that teachers simply accept the textbook's models? Fourth, modelling should be central to teaching and learning because thinking and working scientifically is a core outcome of modern science syllabuses (e.g., Queensland School Curriculum Council, 1999).

### *Why Study Teachers' Ideas?*

A recent study of teachers' modelling knowledge discussed teachers' responses to seven open-ended questions and a 32-item questionnaire (Van Driel & Verloop, 1999). The questionnaire was based on Grosslight et al.'s (1991) protocols and found that chemistry teachers were more concerned with the truthfulness of a model than its utility and most teachers believed that scientists like to use the most advanced models available. In contrast, Coll (1999) found that a traditional chemistry model like the octet-rule was the model of choice for students and researchers alike – even when models with far greater predictive power were available to them. Van Driel and Verloop also found that chemistry teachers were likely to be naïve realists with respect to models and modelling, followed by biology teachers with physics teachers the most flexible. They concluded that "teachers' knowledge of models and modelling in science is often limited, and may include inconsistencies" (p. 1151). Van Driel and Verloop's study relied on survey and questionnaire responses; therefore, this interview-based study provides an interesting methodological and epistemological alternative.

Studying teachers' perceptions of scientific modelling is the fourth phase of a project that began in 1994. First, Grade 8–10 science students were interviewed to identify the range of atomic and molecular models held by middle school students (Harrison & Treagust, 1996). Second, a typology of school science models was developed using the modelling literature and the author's previous and current research (Harrison & Treagust, 1998). Third, a small class of chemistry students was intensively studied for one year as they interacted with a wide range of chemistry models (Harrison, 1997; Harrison & Treagust, 2000, 2001). These studies indicated that many secondary science students are naïve modellers who believe that the popular atomic models used in textbooks and teacher talk are 'right.' Why do students think this way? The answer to this question may lie in the way teachers and class textbooks use models to explain secondary science concepts.

## Design and Methods

### *Theoretical Framework*

Interview is a useful way to probe teachers' perceptions of their practice but it does have limitations. Norman (1983) cautions that "people may state (and actually believe) that they believe one thing but act in quite a different manner" (p. 11). For this reason it should be remembered that all data and interpretations derived from interviews are no more than the investigators' interpretations (Duit & Treagust, 1995). Mindful of these limitations, the interviews were designed to be as comprehensive and flexible as possible. The interpretive mode is equally important and a phenomenological method was adopted (Cohen, Manion, & Morrison, 2000). In Patton's (1990) words, phenomenology "is the structure and essence of experience of this phenomenon [models] for these people," and he argues "that *we can only know what we experience* by attending to perceptions and meanings" (italics in original, p. 69). Making sense of a phenomenon like modelling in schools entails more than just describing the stakeholders views; it involves a search for commonalities and processes of thought and action. For these reasons, the data are first reported in tables and comments, the interview and textbook analysis data are compared and contrasted, and then the interpretations are discussed in the light of relevant literature.

### *Subjects*

Ten teachers from two large public high schools in the Perth metropolitan area were interviewed about their understanding of modelling in science. Each volunteer teacher was paid a $A100 honorarium to compensate them for lost non-teaching time during the interview and to later read and comment on the interview transcript. The schools were selected for their mix of teacher experience and cooperation in previous research.

Four teachers came from School A and six from School B and all were science graduates with specialist science teaching qualifications. Two of the participants were science department heads and one of these teachers holds a doctorate in science education. One teacher had changed from a veterinary science career to teaching and another had an agricultural science background. The teaching experience of the interviewees ranged from 6–25 years with a mean of 14 years and median of 10 years. All 10 teachers teach middle school science and at least one senior subject. At the senior level, four teach biology, two teach chemistry, three teach physics (one of these also teaches senior biology) and two teach senior science.

### *The Interviews*

The interviews averaged 35–40 minutes, were semi-focused and avoided revealing the interviewer's modelling interests until later in the interview because spontaneous

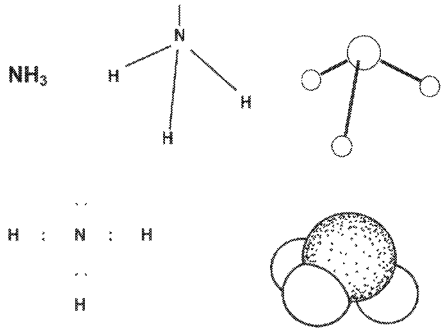


*Figure 2:* Five representations of an ammonia molecule.

reference to models and analogies should be more authentic than cued responses (Treagust, Harrison, Venville, & Dagher, 1996). To start with, each teacher was asked about his/her academic qualifications, years of teaching experience, classes taught in the past and present, and main science teaching interest. This approach elicited interesting ideas from several teachers concerning their philosophy of science and science interests. Once the biographic information was complete, each teacher was asked this question:

> ... moving on to teaching, one of the major difficulties in secondary teaching is explaining science concepts to teenagers because sometimes the concepts are non observable, they're abstract or counter intuitive. Can you think of any recent concept that you've found difficult to teach or explain?

This probe aimed to elicit the favourite explanations, analogies, metaphors or models used by individual teachers. The probe was quite successful with poppet bead models of genes and chromosomes emerging on three occasions (biology teachers), and a detailed analogy of photosynthesis from a physics teacher. This interview orientation was designed to explore whether the teachers spontaneously resorted to analogical models when an alternative explanation was needed; that is, in situations where the students were showing or voicing their inability to understand the science content. In four cases, the teachers chose analogical models early in a series of lessons suggesting that they believed this to be a legitimate way to explain difficult concepts. When questioned further, three of the four teachers supplied cogent educational reasons for their use of analogies and models.

Once this part of the interview had run its course, each teacher was shown a series of analogical models and invited to comment thereon. These models included:

1. a scale model heart or eye;
2. a toy model boat (1:50 scale);
3. a text-book diagram of diffusion across a semi-permeable membrane;
4. five representations of ammonia (see Figure 2); and,
5. a simple tube for an earthworm's gut (Ogborn, Kress, Martins, & McGillicuddy, 1996).

Each teacher was asked to respond to John Gilbert's (1993) four assertions about models. The verbal and written propositions given to the teachers read:

> I have here four descriptions of models taken from the science education literature. It is claimed that models are the main products of science, modelling is part of the scientific method, models are major learning tools in science education and models are major teaching tools in science education. How do you react to these claims for the power of models and modelling?

The teachers responded to most of these propositions and where interesting ideas were hinted at, further questions were asked to solicit reasons and/or examples. This discussion also provided opportunities to explore the teachers' notions about the 'fixedness' of consensus models; that is, whether common textbook models of atoms, cells and plant and animal parts can be modified by the teacher or the students to accommodate their learning needs. The interviewer then asked whether or not the teacher discussed the shared and unshared attributes of models with his/her students (Glynn, 1991). Finally, each teacher was asked if s/he encouraged her/his students to construct models (e.g., a model cell or a model atom) and when the answer was affirmative, the teacher was asked to elaborate.

Ample opportunities were provided for the teacher to lead the discussion towards his/her favourite analogies and models and this occurred on at least six occasions. Indeed, three teachers were enthusiastic about their personal models and expounded their 'owned' models.

Each interview was transcribed verbatim and read against the audio-tape to identify and correct errors. The transcript was returned to each teacher for validation and four teachers returned their transcript with corrections and qualifications. The transcripts were scrutinised to identify the key issues and concepts, and the responses were collated and classified. The modelling categories that emerged included each teacher's repertoire of analogies and models, legitimacy to construct and/or modify models, perceptions of the ammonia models, can models be simplified and/or exaggerated, discussing where models break down, responses to Gilbert's (1993) propositions, and views on mathematical, theoretical and multiple models. Last of all, a modelling level was proposed for each teacher based on Grosslight et al.'s (1991) descriptors.

## Data, Interpretations and Findings

The interview data are summarised in Tables 1 and 2. The text that follows discusses with excerpts, the ten teachers' spontaneous comments and answers to the interview questions.

Table 1
*Summary of the Teacher Response in the Interviews.*

| Criterion | Interview responses | | | | |
|---|---|---|---|---|---|
| | Colin | David | Hans | Steve | Karen |
| Subject specialty | Chemistry and middle school science | Physics and middle school science | Chemistry and middle school science | Physics and some middle school science | Physics, Biology and middle school science |
| Major interest | "all things chemical" | "a passion for science" | Middle school science | Science in general | "to make sense of the world through the eyes of science." |
| Models volunteered | Limited repertoire and infrequently uses models "I don't have a kit of [models], I just build it up as I go" | 5 concrete or scale models e.g., Solar system models;<br>6 process models e.g., Role-play models (light), | Only one model despite five requests.<br>"I tell [students] what [the models] are" | 3 concrete or scale models e.g., Planetary model of an atom;<br>3 process models e.g., reaction mechanisms | 6 concrete or scale models e.g., diagrams are models;<br>4 process models e.g., models as stepping-stones |
| Models can be changed to suit your ideas? | Maybe, but "you cannot modify accepted models" | It is legitimate to change models | "this is the model that all students should learn" | Yes, but consensus models are definitive, not to be changed | Yes, this is the essence of learning science |
| Students can build and modify models. | Yes, but we don't do it. | Yes, but we don't do it. | In middle school only | Yes, "students have fertile imaginations . . ." | Students encouraged to build and modify models |
| Shared–unshared attributes | Not discussed | Yes, must show where models break down | No | Yes | No |
| Uses multiple models | Yes | Yes, but needs to increase their use | Yes | Prefers one model per concept, tells students which is right | Yes |

Table 1
*(Continued.)*

| Criterion | Interview responses | | | | |
|---|---|---|---|---|---|
| | Jane | Ian | Cindy | Graham | Terry |
| Subject specialty | Biology and middle, school science | Senior Science and middle school science | Biology and middle school science | Senior Science and middle school science | Biology and middle school science |
| Major interest | Not discussed | Teaching science to low achievers | Making sense of the world using animations | Teaching science to low achieving students. | Horticulture and environmental issues |
| Models volunteered | 4 concrete or scale models e.g., bell-jar diaphragm and lungs; | 3 concrete or scale models e.g., poppet bead genes; | 4 concrete or scale models e.g., a model heart; | Limited model repertoire “No, I’d say I don’t use models, what are they?” | 3 scale models e.g., model eye; |
| | 3 process models e.g., building food chains | 5 process models e.g., breeding role plays; and Likes video animations. | 4 process models e.g., simulates particle processes and animations | Interview cues elicited 4 scale models | 4 process models e.g., drainage analogy for lymphatic system; models are thinking tools, likes computer models. |
| Models can be changed to suit your ideas? | There is “one best composite model for each phenomenon.” | Yes “if you make your own model you tend to find out what works best” | Yes, models should be modified as a concept develops | Likes to use models that can be extended | Limited – in food webs you can change organisms |
| Students can build and modify models. | “Make a model? Most models I use are made for me.” | Give the students a simple model and try to enhance it | Yes “play with and personalise models” | Year 9 students build a model atom. | No, but might be useful |
| Shared—unshared attributes | Yes, negotiates where the model breaks down | No, rarely discuss this with students | Yes | No | Yes |
| Uses multiple models | Yes | Yes, with reservations | Yes | Not discussed | Yes, this is high-level thinking |

Table 2
*Teachers' Opinions about the Four Roles of Models in Teaching and Doing Science (Gilbert, 1993).*

| "Models are. . ." | Teachers' opinions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | David | Karen | Steve | Ian | Cindy | Jane | Hans | Graham | Colin | Terry |
| Main products of science | ✓ "models are the big theories" | ✓ | "Maybe ... I'm not sure" | ✗ | "only to explain to other people" | ? | ✓ | "I could argue both ways on that" | ✓ | ✓ |
| Major tools of science | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Important learning tools | ✓ | ✓ | ✓✓ | ✓✓ | ✓ | ✓ | "I'm not too sure, it depends" | ✓ | ✓ | ? |
| Important teaching tools | ✓ "but we do lack resources" | ✓ | ✓✓ | ✓✓ | ✓ | ✓ | ✗ | ✓ | ✗ | ? |
| Modelling level (Grosslight, Unger, Jay, & Smith, 1991) | 3 | 3 | 3 | 2/3 | 2/3 | 2 | 2 | 2 | 1/2 | 1/2 |

*Note*: ✓✓ indicates strongly agrees; ✓ indicates agrees; ? indicates unsure; ✗ indicates disagrees.

*What is Modelling*

At an appropriate juncture in the interview, each teacher was asked to elaborate his/her understanding of modelling in science. A typical question was: "I notice that you talk about model atoms. I'd be interested to know what your concept of a model is, the way that it's used in science?" David offered this perception:

> A model I see is something that is a representation to simplify a difficult concept. Perhaps something we don't use often enough. . . . In chemistry it works well, we can have a representation to display something that's incomprehensible . . . a representation of what we don't [understand].

David's notion of "something that's incomprehensible" arose from a problem that occurred in his naked-eye astronomy class the previous night. Venus, Mercury, the Moon and Jupiter were very much aligned with each other and one student wondered, how this could be? He added:

> If I had a representation . . . of [planetary motion] she could understand because they've seen posters of the planets in these big almost circular orbits. But she had great difficulty [understanding] that Earth was here and we were all orbiting in basically the same plane . . . a physical model for the solar system, a model made of plastic that models what the solar system looks like in a very distorted sort of proportion . . . would be a good way of explaining that.

When the two chemistry teachers were asked this question, Hans found that he made limited use of models "no . . . not a lot" and, "[models] are not a really major teaching tool at all." However, when asked about multiple models, Hans proposed that:

> . . . you use models to assist people in learning but my idea is you should expose people to as many different models as possible because people learn in different ways and one model may be acceptable to a certain number of people but another model, it may not be acceptable.

Alternatively, Ian who mostly teaches science to low achievers, explained models this way:

> I use the word analogy but I'd also point out that [a model] is a simplified plan or a simplified analogy, it's a simplification of a difficult situation where simplifying makes it easier to understand initially and from that simple understanding you can then take the person to a higher level of understanding if you wish . . .

Steve – a physics teacher who works with Ian – pointed out that:

> A model is a familiar illustration from which [students] can go from known to unknown, simple to complex, something they can visualise [and] focus on which leads to something more abstract. In science we use a lot of models . . . concrete models . . . abstract models, a concrete model I use is the factory model to explain photosynthesis in a leaf . . .

Ian twice spoke about the benefits of designing your own models for specific purposes – particularly for low achievers. On one of these occasions he explained his ideas this way:

I think if you make your own model you tend to find that it works better, because you've thought it through right from nothing, whereas somebody else's model ... if you don't know how it was developed to that point you can't use it well.

This view was endorsed by Karen but she told how she encourages her students to construct and use some of their own models to solve problems: indeed, she does not insist on students using hers or the textbook's model:

using a different model, students get the same result, get the same understanding from it, I really don't mind because I believe in ownership of your learning ... Change models to suit your uses? ... Yes, definitely ... as long as your changes are not incorrect [like] changing the labels on the heart ... I simplify diagrams all the time, taking out what I think the kids do not need to know.

The way Karen matter-of-factly treats diagrams as models is interesting. A different perspective came from Cindy who, when asked to define a model, responded with a more technical explanation.

A model is a device that shows you how an object is structured or built, or put together or shows you how it functions ... or shows you how things work. [Models] make it easier for you to understand, it is either an enlargement of something that is too small to be seen easily or it enhances the process and lets you make predictions ... a model is like a prop. ... Simulations are very important in my opinion. All of this is my opinion. ... No, the model isn't the reality, no.

The predictive aspect of modelling also emerged in Steve's interview. From Steve's point-of-view, analogies and models utilise students' imagination and act as conceptual bridges (Clement, 1987).

Students have fertile imaginations ... a predictive capacity for the imagination to understand a concept. ... You climb on the model and look at the concept, it becomes more clear ... a model maybe is like the telescope [or microscope] if you like, what is not visible to the naked eye becomes visible through a telescope [or microscope]... It's also like a stepping stone, you go from a known to an unknown.

This bridging effect is a feature of 'bridging analogies' and bridging analogies are a fruitful way to maximise the effect of multiple analogical models (Clement, Brown, & Zeitsman, 1989). This issue is explored further in the *Discussion section*.

Cindy expanded her simulations-model and expressed a preference for using animations to explain nonobservable science processes like diffusion, sound and hearing, and cellular transport. The way she described them, Cindy's animations are stripped of all unnecessary information – leaving minimum 'noise' – as proposed by Johnstone and Al-Naeme (1991).

I find animations are very, very good and particularly if they're kept very simple and you can even use them for things like [diffusion and] magnetism – animating the domains – what I'm saying is the processes are the important part and I think the animation shows the changes. I think a static model can only show you so much but a moving model actually shows a process. ... The secret to success is to actually keep it very simple. ... A good model is something that repeats [the concept] in different contexts.

Cindy also was attracted to over-simplified models like the simple tube earthworm gut used in Ogborn et al. (1996). She argued that teachers should customise commonly used models to suit their purpose and audience.

Similarly, Terry volunteered simulations as his preferred model, he called this type of modelling "hands on playing." He also believed that models are thinking tools that "help to simplify concepts." His example of a simulation was a gene pool change; for example, the favourable selection of dark skinned people in sunny climates.

This summary of the teachers' comments yields a suite of model attributes. Three teachers believe that models are simplifications (Cindy, Ian and Steve) while David sees them as proportionally distorted and Karen likes enlarged or exaggerated models (Ogborn, Kress, Martins, & McGillicuddy, 1996). Hans insists on consensus on model form and use, Steve values familiar analogs (Glynn, 1991), Karen likes models that can be modified to develop ideas (Grosslight, Unger, Jay, & Smith, 1991), Cindy prefers multiple models (Harrison & Treagust, 2000) and Ian feels that effective models are personal constructions (Harrison & Treagust, 1998). The references to the literature indicate that these are desirable features of in-class modelling.

### *Gilbert's Propositions and Modelling Level*

Given these attributes, and the Table 2 data showing that all 10 teachers accept models as major tools of science, it is surprising that three teachers disagreed or held reservations about models being the main products of science. Indeed, two teachers were unsure whether models are important learning tools and three teachers were not prepared to endorse models as major teaching tools. Overall, six of the 10 teachers disagreed (or were doubtful) about at least one of Gilbert's (1993) propositions. The data may signal differences in some teachers' philosophy and epistemology.

Gilbert's propositions are generally compatible with Chalmer's (1999) account of the nature and philosophy of science – particularly with reference to evidence, theory and ways to represent scientific knowledge. It seems helpful to compare responses on Gilbert's propositions with Grosslight et al.'s (1991) epistemological modelling levels. All Level 3 modellers (Darren, Karen and Steve – Table 2) saw models as flexible thinking tools and agreed with all four of Gilbert's propositions. Indeed, David declared that "models are the big theories" of science. As we move down the modelling scale – Levels 2/3, 2 – the disagreements with and doubts about the propositions gradually increase. That is, at lower modelling levels, models are more likely to be fixed and "right" than flexible thinking tools. It should be remembered that Gilbert's propositions were part of the data corpus on which the level decisions were made and caution should accompany these interpretations.

Steve and Graham were ambivalent about models being the main products of science. Steve's uncertainty is puzzling given his very positive views about the desirability of students using models as thinking tools. Cindy's view also is curious.

She sees models as important explanatory products for others but not herself; yet she promotes the use of animations and simulations and sees models as conceptual props that lead to predictions. Graham's ambivalence was not qualified nor did his other comments illuminate this statement. Further research into the ways teachers view Gilbert's assertions is therefore warranted.

In the case of the two chemistry teachers (Colin and Hans), their lower modelling levels may be explained by their insistence that they do not have a repertoire of models to use. If they deny the existence or utility of models, it is unlikely that they will use them as in-class thinking tools. Reluctance by some other teachers to use models may relate to the unpredictable way that students interpret models and analogies. This problem of "where do models break down" is therefore discussed in the next section.

*Models and their Limitations*

All the teachers were asked their perceptions of the model boat and most described it as scale model. Only David identified its unshared characteristics by pointing out that if scaled up, the boat would capsize because the sails and rigging – being of the same materials – made it top heavy. Hewitt (1992) also identifies functional incompatibilities between scale models and the object modelled.

Two other interviewees – David and Steve – both identified and volunteered multiple instances where models break down. They recognised the importance of helping students explore the shared and unshared attributes of classroom models (Duit, 1991; Glynn, 1991). At some point in the interview, teachers volunteered their views or were asked about the limitations of models and analogies. Steve was the most forthcoming and on four occasions insisted that teachers must point out to their students where models and analogies break down. Five of the teachers (three biology and two physics teachers) were vigilant in this direction. Five teachers did not volunteer the need to discuss unshared analogical attributes and when asked, four said no, they did not perform this task. The issue did not arise in Colin's interview. Neither of the chemistry teachers performed this task while about half the biology and all the physics teachers did so.

Duit (1991), Glynn (1991) and Treagust, Duit, Joslin and Lindauer (1992) all point out that it is rare for teachers to identify where analogies break down in the classroom. Over the past ten years, substantial effort has been applied to encourage Perth teachers to identify the shared and unshared attributes of analogies with students. When it is realised that these authors' research outcomes were disseminated in local schools, this study's findings suggest that a significant number of teachers have responded to the challenge.

*Model Repertoires and Teaching Domain*

Eight of the 10 teachers volunteered an extensive range of models with the greatest range and similarity being the biology teachers' models. The biology teachers offered a mean of seven models each (range: 4 to 9). All five biology teachers talked about scale models of hearts, eyes and skeletons; four of the five volunteered food chains, webs, pyramids and energy flows; two teachers discussed gene and chromosome models and also classified diffusion diagrams and demonstrations as models. Four of the five biology teachers told how they simulated biological concepts using everyday processes; for instance, a household drainage system is like the lymphatic system and role plays were used to simulate meiosis and fertilization and to track the inheritance of specific characteristics.

Again, four of the five biology teachers volunteered one physical science model or analogy. Joan said, "a mole is like a dozen eggs"; Ian devised an elaborate nuts and bolts model for elements and bonding; Cindy suggested an animated magnetic domain model and Graham offered a car cooling system analogy for homeostasis.

Though models are less likely to be used in physics textbooks, the three physics teachers – David (11 models), Steve (6 detailed models in the longest transcript) and Karen (10 models) – were the teachers who used the greatest number of models and two of these teachers used models across subject areas. For instance, Steve opened with his factory analogy for photosynthesis in leaves and Karen commenced with the poppet bead chromosome model and later talked about soil erosion models. Both Karen and Steve delved into the epistemology of modelling – Steve talked about its predictive power, student imagination and analogical stepping stones and Karen also used the stepping stone metaphor.

Surprisingly, the two teachers who volunteered the fewest models – just one model each – were chemistry teachers. This is curious because the parallel analysis of model variety and frequency in science textbooks shows that the highest incidence of models occurs in chemistry textbooks! Colin said: " I don't have a kit of [models], I just build it up as I go." Hans mirrored this comment: despite five requests or opportunities to present models, he offered just one and that was a Grade 9 assignment to build a model atom. In contrast, both Colin and Hans later agreed that the use of multiple models in chemistry is desirable. It is arguable that the only way submicrosopic chemistry concepts can be represented is through analogical models (Gabel, Briner, & Haines, 1992). An explanation for chemistry teacher's lack of sensitivity to models and modelling is that chemical models may have become an unconscious part of their chemical thinking.

But both chemistry teachers were unwilling to manipulate models – "you cannot modify accepted models" (Colin); and, "this is the model that all students should learn" (Hans) suggesting that chemistry models and teachers' perceived realities are equivalent. The notion that chemical models may become ontological realities warrants substantial research by exploring teachers' and students' perceptions of atomic models.

*Summary*

The high incidence of models volunteered by seven of the teachers – an average of eight models each – suggests that these teachers' students meet an effective range of scientific models. The equal representation of concrete and scale models versus process models in these teachers' repertoires means that their students are exposed to thinking models. Two very encouraging aspects of the data are the preference shown by four teachers for simulations, animations and role play models, and the fact that five of the teachers regularly explain to students where the current model breaks down.

Taken together, the views of the 10 teachers at the two schools comprise a rich, comprehensive and creative view of modelling. Collectively the teachers' model use satisfies almost all the recommendations in the literature for effective model use; but only three teachers individually met the expert modeller criteria. Furthermore, only five of the ten teachers were deemed to be Level 3 or Level 2/3 modellers. The criteria for Grosslight et al.'s modelling levels suggest that Level 2 and below is a problematic foundation for teaching secondary science.

It is now appropriate to analyse the models found in the teachers' science textbooks. This will enable a comparison of the teachers' perceptions of their model use with the textbooks from which they plan and teach. These data will help answer the study's second question and may shed light on the apparent low level of model use by chemistry teachers.

## Textbook Models

Teachers often use their textbook to plan work programs and the content of their science lessons (Sanchez & Valcárcel, 1999). Indeed, an important teacher criterion for selecting a textbook is the textbook's utility as a lesson planning and teaching resource. Textbooks also act as surrogate teachers when the teacher is unavailable – teachers are aware of this use and encourage students to use the textbook as a learning resource. But textbooks differ widely in the way they depict science, its objects and concepts; and in the way they use scientific models. Anecdotal evidence suggests that many teachers are careful to teach science in ways that are compatible with the students' textbook descriptions and explanations; therefore, research should explore links that might exist between textbook model use and the teachers' views about models and modelling.

The number and variety of models used in textbooks complicates this task; consequently, a means for classifying textbook models was needed. The typology of science models developed by Harrison and Treagust (1998) appeared well suited to the task. The typology shown in Figure 3 organises science teaching models along two dimensions: the horizontal left-to-right dimension ranges from concrete to abstract and the vertical top-to-bottom dimension ranges from simple analogy to multiple analogy. The eight categories are described under three headings of *Information-rich Models*, *Analogical Models that Build Conceptual Knowledge* and *Models Depicting Multiple Concepts and/or Processes*.

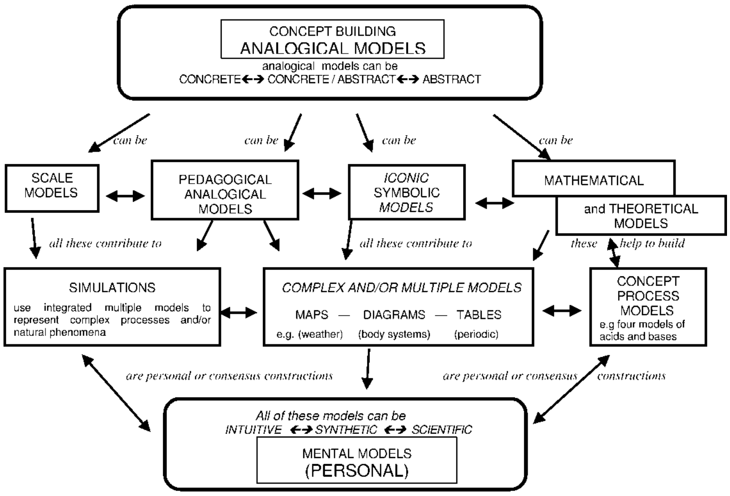


*Figure 3:* The model typology used to analyse textbook models (Harrison & Treagust, 1998).

*Information-rich Models*

*Scale models*

Scale models of animals, plants, cars and buildings are used to depict colour and external proportions but rarely show internal details, functions and use (Black, 1962), nor are they made of the same materials as the target. Size-for-size, a scale model bridge is stronger than the actual bridge (Hewitt, 1992). Scale models are often toy-like and this realism may obscure the unshared analog – target differences.

*Pedagogical analogical models*

This is a family of explanatory models used in teaching and learning and includes some scale models. They are "analogical" because the model shares information with the target (Glynn, 1991) and "pedagogical" because they are used to teach about nonobservable entities like atoms and molecules. One or more attributes dominate the analog's structure (e.g., balls and sticks in molecular models, Keenan, Kleinfelter, & Wood, 1980). Because analogical models display point-by-point correspondences between the analog and the target for certain attributes, models can be simplified or exaggerated to highlight conceptual attributes. This category can be elaborated as –

*Analogical Models that Build Conceptual Knowledge*

*Iconic and symbolic models*

Chemical formulas and equations are symbolic models of compound composition and chemical reactions (Feynman, 1994; Pimentel, 1963). Formulas and equations are so embedded in chemistry's language (Sutton, 1992) that students and teachers may mistake these explanatory and communicative models for reality. Formulas and equations need to be interpreted; for instance, carbon dioxide – ($CO_2$) needs transforming into OCO, O=C=O and so forth.

*Mathematical models*

Physical properties and processes (e.g., $k = PV$), can be represented as mathematical equations and graphs depicting conceptual relationships. (e.g., exponential decays, etc.) (Black, 1962). Kline (1985) insists that mathematical models are the most abstract, accurate and predictive of all models. However, models like $F = ma$ only function in frictionless situations that rarely exist in classrooms and this limitation should be identified. It also is important that students construct verbal or written qualitative explanations for mathematical models (Hewitt, 1992).

*Theoretical models*

Analogical representations of electro-magnetic lines of force and photons (Gee, 1978) are theoretical models because they are human constructions describing abstract theoretical ideas. Models like the kinetic theory's explanation of gas volume, temperature and pressure belong to this category (Keenan, Kleinfelter, & Wood, 1980). Oversimplifying kinetic theory particles as perfectly elastic space-filling spheres qualifies that part of the model as a scale model. Some phenomena blur the boundary between theoretical and mathematical models (Black, 1962).

*Models Depicting Multiple Concepts and/or Processes*

*Maps, diagrams and tables*

These models help students visualise objects, patterns, pathways and relationships that cannot be observed directly (DiSpezio, 1994; Newton & Joyce, 1990). Examples are the periodic table, weather maps, circuit diagrams, pedigrees and food webs. It is important to recognise the simplified and exaggerated nature of all or part of these two-dimensional models. Individual students interpret diagram items and colours differently and some students even think that chlorine atoms are green (Ingham & Gilbert, 1991).

*Concept–process models*

Many science concepts are processes; so how do teachers explain abstract processes to students who think in concrete terms? Teachers and textbooks use multiple concept models of acids and bases and oxidation–reduction (Carr, 1984; Garnett & Treagust, 1992). Which is oxidation? The gain of oxygen, loss of hydrogen, loss of electrons, increase in oxidation number or all of these? Students often cannot understand why the teacher has introduced another model with an opposite action (loss instead of gain) for the same process. Students tend to memorise the rules and hesitate to explore the reasons for characterising oxidation as both gain and loss. The most effective explanation for the refraction of light uses concept–process models like wheels or marching soldiers moving from a hard-to-soft or soft-to-hard surface (Harrison, 1994).

*Simulations*

Simulations and animations are a unique category of multiple dynamic models. Simulations model complex and sophisticated processes like aircraft flight, global warming, nuclear reactions, and population dynamics. Simulations enable novices and researchers to develop and hone skills without risking life and property and also may include "virtual reality" experiences (e.g., computer games and computer-based interactive multimedia). The realism of many simulations masks their analogical nature and encourages students to visualise the simulation as reality.

## *What Counts as a Model in a Textbook*

The two-dimensional format of textbooks limits the ways authors can represent objects, processes and concepts for their readers. Pictures, stories and prosaic analogies must suffice where a three-dimensional model would be used in class (e.g., a model ear or a tetrahedral shape for methane). Superficially, this means that all textbook models could be called maps, diagrams or tables; however, interpretations of the authors' intentions in using a particular model have guided the classifications shown in the tables of textbook models. For instance, a picture of a ball-and-stick molecule is interpreted as a pedagogical analogical model (so too is a picture of an atom). Diagrams of body parts and cells where the structure is scaled are deemed to be scale models and diagrams of magnetic fields are called theoretical models. Mathematical models are easy to identify by their equation format or presentation as graphs and iconic models pose few problems (chemical formulae or force representations). One area where discrimination is necessary and sometimes appears arbitrary is deciding whether chemical and physics equations are iconic or theoretical models. It is important that the reader understand that the above typology is adhered to as closely as possible in the subsequent discussions of textbook models.

*Models used in senior secondary chemistry textbooks*

The textbook used by most chemistry classes in Western Australia is *Foundations of Chemistry* (Garnett, 1985); therefore, the incidence of atomic, molecular and special models in this textbook was analysed and the results presented in Table 3. The table does not use all the categories discussed above because chemistry uses

Table 3
*Analysis of Model Use in a Popular Grade 11–12 Chemistry Textbook (Garnett, 1985).*

| Chemistry Textbook | Model Types | | | | | | |
|---|---|---|---|---|---|---|---|
| | Iconic symbols and equations | Pedagogical analogical models | | | Mathematical and theoretical | Maps, diagrams & tables | Specific analogical models |
| | | Space filling | Lewis electron dot | Lewis structural | | | |
| *Foundations of chemistry* (Garnett, 1985) | 400+ | 35 | 29+ | 74+ | 30 (math.)<br>7 (theory)<br>15 (mixed) | 28 | 25 (none explained) |

many special models. *Foundations of Chemistry* was used by each chemistry teacher interviewed in the study.

Chemical models are used to explain or represent chemistry concepts. The most common models are symbols and equations and these feature in every chapter of Garnett (1985) except Chapter 1; and by the latter half of the book symbols, formulas and equations dominate most pages. Iconic notations are chemistry's propriety language and it seems that authors assume that students understand their meaning and use in describing and explaining chemical processes. The incidence of space-filling, Lewis electron-dot and Lewis structural models are tabulated in columns 3–5 of Table 3 and a pattern is evident – space-filling models dominate the early chapters (2–15) but give way to Lewis structural models in the covalent bonding and organic chemistry chapters (7, 21–25). Lewis electron-dot models were mostly limited to Chapter 7 where they are used to explain covalent bonding.

Chemistry may be the most model-laden of the school sciences yet in this textbook only five representations are specifically labelled as models and the modelling process is not discussed. The five models are "a model of matter" (p. 21), "a model for the structure of an atom" (p. 22), "the Bohr model of the hydrogen atom" (pp. 65–66), "the quantum mechanical model" (p. 68), and "a model for sugar dissolving in water" (p. 201). Many other models equally deserve being called a model; for instance, graphical representations of periodic trends, the Pauli exclusion principle and reaction rate models; equilibrium states; and the well-known concept–process models of acids and bases and oxidation-reduction (Carr, 1984). Exaggerated or simplified models are used for electrical conduction (p. 89), ionic lattices (p. 100), polar bonds (pp. 111–114), the electromagnetic spectrum and pH scale (logarithmic or mathematically compressed – do readers know why?), corrosion (p. 403), sigma and pi bonds (pp. 441–443) and detergent action and polymer structure (pp. 503, 510). On pages 437–440, five unexplained multiple models of the same molecule are used side-by-side – space-filling, ball-and-stick, Lewis electron-dot, structural formula and word descriptions. This is an opportunity to explain the comparability of the molecular models but it is missed. Do the authors assume that students understand multiple representations (research says this is unlikely) or is there a confidence that the teacher will explain the shared and unshared attributes of each model? Only two chemistry textbooks of all those surveyed over the past five years discuss the shared – unshared attributes of molecular models with readers. These are Keenan et al. (1980) and Zumdahl (1989). Both of these textbooks are college chemistry textbooks – a level higher than senior secondary chemistry cousins – yet the authors do not assume that college students understand the similarities and differences present in multiple models of the same entities. So why do we assume that Grade 11–12 students do not need this help?

To be fair, the pattern identified in *Foundations of Chemistry* is repeated in many modern secondary chemistry textbooks and the last item – the depiction of four or five alternative models side-by-side is found in older textbooks (e.g., Parry, Dietz, Tellefsen, & Steiner, 1970, p. 41). However, Parry et al. (1970) and Pimental (1963) do take time to explain some aspects of the modelling process. In Chapters 1 and

2, Parry et al. elaborate their modelling style by saying that the "super-rubber ball" model helps us construct a mental model of gas behaviour:

> when the explanation involves a real physical system (such as bouncing balls), we call it a model; when it involves more abstract ideas linking model and system (e.g., a mathematical equation) we call it a theory. (p. 21)

This paper's typology would call the latter case a theoretical model. They then add,

> A useful model points to new directions of thought, suggest new experiments and can be expanded or modified to account for the results of many new studies. A useful model is the heart of scientific thought. (Parry et al., 1970, p. 21)

*Foundations of Chemistry* also contains 52 models that are classified as mathematical, theoretical or mixed mathematical–theoretical models. The mixed category contains models like the graphical representation of "atomic radii of the first twenty elements" and the "number of outer energy level electrons of the first twenty elements" (pp. 136–137). The plots of atomic radius and outer shell electrons against atomic number respectively identify periodic groups and chemical families. The constructs of periodicity and chemical similarity (theoretical models) are easily recognised in the graphical representation of the elements' attributes (a mathematical model). Another mixed model is the equilibrium constant: it is a mathematical statement of reacting proportions yet it describes and explains a dynamic equilibrium and is highly predictive for changes to the reacting system. This phenomenon lends weight to the argument that mathematical and theoretical models are not separate constructs but are artifacts of the chosen mode of representation.

### *Models in Senior Secondary Biology Textbooks*

Analysing the biology textbooks used by the teachers was complicated by the use of two textbooks. School A chose *The Nature of Biology – Book 1* (Kinnear & Martin, 1992) while School B employed *Senior Biology* (King & Sullivan, 1991). The pattern of model use in each book – shown in Table 4 – is substantially equivalent but there are many more models in each category in *Senior Biology* than in *The Nature of Biology.* It also was necessary to add a model type – experimental models – because both textbooks modelled scientific evidence in an experimental format (e.g., phototropism in plant shoot tips, Pasteur's experiment).

*Senior Biology* has 68 scale models and 185 pedagogical analogical models whereas *The Nature of Biology, Book 1* uses 39 and 85 respectively in a similar sized book. This difference stems from the communicative approach used in each book. *Senior Biology* is basically a book of diagrams; that is, it is an information resource and contains few prosaic explanations. With minimal text, its pages contain up to six black-and-white diagrams of plants, animals, parts of organisms, life cycles and processes like meiosis, gas exchanges and digestion/absorption. The line diagrams

Table 4
*Frequency of Model Use in the Nature of Biology–Book 1 and Senior Biology.*

| Biology textbook | Model types | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scale models | Exptl. models | Pedagog. analogical models | Iconic symbolic | Math. models | Theory models | Maps, diagrams tables | Concept process models | Simul-ations |
| *The Nature of Biology – Book 1* (Kinnear & Martin, 1992) | 39 | 2 | 85 | 19 | 30 | 9 | 86 | 24 | 3 |
| *Senior Biology* (King & Sullivan, 1991) | 68 | 13 | 185 | 29 | 42 | 12 | 117 | 27 | |

are accurate and contain much detail – especially anatomical information. On the other hand, *The Nature of Biology, Book 1* uses colour pictures, simplified and exaggerated diagram-models and a variety of prose descriptions and explanations. It weaves an ecological story in which concepts dominate and anatomical detail is used only where it is needed to illustrate the conceptual story. Kinnear and Martin employ the five kingdoms model, there is liberal use of photographs and almost all the examples depict Australian flora, fauna and environments. Like other recent textbooks (e.g., *Biology: The Common Threads*, Australian Academy of Science, 1990), *The Nature of Biology, Book 1* contains boxed vignettes about the work of scientists and the application of important concepts to modern life.

Another source of biology teachers' scientific knowledge in Western Australian schools are the resource sets of supplementary textbooks and reading materials for Biology and Human Biology classes. Schools also are likely to change biology textbooks more often than they change chemistry textbooks and the range of suitable biology textbooks is quite large. Indeed, the year following the interviews, School B replaced *Senior Biology* with a more modern biology textbook.

The review of senior science textbooks found four biology textbooks in which the authors explain the role of models and modelling in understanding science ideas.

> ... a scientific model is a simplified representation of an idea or process. ... Once a model has been developed, it can be used in a number of situations ... a diagrammatic representation of the structure of a cell, is also a model. Models may be diagrams, flow charts, or physical models such as a model of the atoms in a protein. Scientific models often have to be modified as new data are collected. (Newton & Joyce, 1990, p. 9) (current school textbook)

> When a scientist is attempting to interpret natural events, he (sic) often finds it useful to express his ideas in a simple way, as a scientific model. The model is thus a simplified representation of the idea. For instance, the relationship between stimuli, receptors and effectors ... can be expressed as a model in the way shown in Figure 19.14. ... Many different animal responses fit this model. The model is a kind of generalisation that we can use to help interpret many different observations (Australian Academy of Science, 1973, pp. 419–20) (older school textbook)

> Models are like analogies in that they attempt to represent the unfamiliar in terms of the familiar (p. 178). ... Hypothetical models should help ... generate other hypotheses and suggest experiments with which to test them. It is not necessary for a model to bear any resemblance to reality. (Baker & Allen, 1977, pp. 1086–1089) (older college textbook)

> A model [is] a simplified view of how the components of a structure operate that is consistent with previous scientific knowledge and also offers new insight. A model often comes from comparing a process that is not understood to one that is ... the scientist constructs a model that suggests how the phenomenon works. (Tobin & Dusheck, 1998, p. 3, current college textbook)

In *The Nature of Biology – Book 2,* Kinnear and Martin (1992, p. 10) elaborate "the fluid mosaic model" for membrane action. They explain that as the "sandwich model of the cell membrane ... did not account for all the known behaviours of a cell membrane" a better model was developed. They discuss how the fluid mosaic model "suggests" a better membrane structure and function and why it is "presently accepted" as a better model. Later (pp. 54–55) they model enzyme action using analogical models, 'lock-and-key' ideas, graphs and experimental details. Using this paper's typology, their multiple model of enzyme action is best classified as a concept process model.

It is noteworthy that of 12 Australian senior biology textbooks published after 1990, not one discusses modelling other than Kinnear and Martin. A perusal of the list of modelling citations suggests that while some older Australian biology textbooks did discuss model-based thinking this approach has been discontinued. Many recent biology textbooks are published for local audiences (e.g., one state's syllabus) and resemble enhanced sets of teaching notes. They are often black-and-white publications (three in 1999), have few photographs, are dominated by line diagrams and seem unlikely to motivate students. A significant shortcoming lies in their representation of science as a simple linear or cyclic process and their use of many unexplained models. In contrast, research recommends that students learn science more effectively when interest is high (Pintrich et al., 1993) and when their prior conceptions are actively factored into the learning processes (Osborne & Freyberg, 1985).

In concluding these remarks about model use in the textbooks available for Grade 11–12 biology courses in Australia, there is evidence that some authors recognise and discuss the role of models in the scientific enterprise and that they occasionally discuss with their readers the processes and advantages of modelling scientific processes. It should be noted, however, that there is no evidence of biology textbook writers exploring the limits of their models with their readers. As with secondary chemistry textbooks, there seems to be an implicit assumption that readers – students and teachers – are competent interpreters of analogies and models. It is hoped that these findings will stimulate future textbook writers to include discussions about modelling because it is the "heart of scientific thought."

### *Models in Senior Secondary Physics Textbooks*

As might be expected, equations are common in the physics textbook used by the teachers in schools A and B. The main textbook in the two schools, *Physics One* (De Jong, Armitage, Brown, Butler, & Hayes, 1990), was analysed in the same way as the chemistry and biology textbooks and its model types and totals are presented in Table 5. *Conceptual Physics* (Hewitt, 1992) was analysed for comparison because it is a popular reference textbook and for the distinctive way it uses models and analogies. The model types and frequencies in *Conceptual Physics* are included in Table 5. The emphasis in *Physics One* on mathematical explanations is replaced in *Conceptual Physics* by an emphasis on pedagogical analogical models. Indeed, it was Hewitt's use of analogical explanations that helped Glynn (1991) develop his teaching-with-analogies model. Unlike most other textbooks, Hewitt makes explicit the limitations of some of the analogies he uses. This characteristic was not found in any of the reviewed secondary biology, chemistry and physics textbooks. The other

Table 5
*Frequency of Model Use in a Popular Grade 11–12 Physics textbook.*

| Textbook | Model types | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Scale models | Exptl models | Pedagog. analogical models | Iconic models | Math. models | Theory models | Maps, diag, tables | Concept process models |
| *Physics One* (de Jong et al., 1990) | 9 | | 49 | 24 | 58 eqns<br>75 graphs | 6 | 2 maps<br>45diag<br>33 tables | 8 |
| *Conceptual Physics* (Hewitt, 1992) | 12 | 4 | 150+ | 15 | 24 eqns<br>32 graphs | 26 | 3 maps<br>120diag<br>14 tables | 6 |

significant difference is the absence of calculations in *Conceptual Physics* compared to *Physics One.* Again in fairness, it should be noted that *Physics One* depends far less on calculations than previous textbooks like *Fundamental Physics* (Anderton, 1983).

Hewitt (1992) explicitly identifies some of his analogies and models and does discuss the value of models, albeit, late in the textbook (Chapter 38). In his discussion of atoms and the dual nature of light, Hewitt says that

> To visualise the processes that occur at the submicroscopic realm we construct models ... the planetary model ... suggested by the Danish physicist Niels Bohr in 1913 ... has been replaced several times over by models that give progressively better results but become progressively more abstract. Old models sometimes steer us off the track in our investigations of nature and sometimes they provide a scaffolding that allows us to progress to more complicated models. ... The model of the atom has evolved from the Bohr planetary model ... to the modified model with de Broglie waves ... to the mathematical model (the Shrödinger wave equation). (pp. 584–594)

Hewitt develops this ten-page discussion of electron energy levels and spectral models using explanations and eight illustrated analogical models. In light of his frequent use of pedagogical analogical models (e.g., wheels changing direction as they roll from a rough to a smooth surface) his modelling discussion seems more suited to the textbook's opening chapters.

## Discussion

It is timely to revisit the research questions: How do teachers think about the models they use to represent scientific objects and processes? and, Are there similarities between the way textbooks represent models and the way teachers think about and say they teach with models?

The study's notable finding is the difference between the chemistry teachers' sparse repertoire of volunteered models and the plethora of models found in their textbook. When asked about models, Colin and Hans recalled few models yet when presented with the five ammonia models did not hesitate to offer the order in which they used formulas, ball-and-stick, space-filling, Lewis electron-dot and structural models in their teaching. Both were definite that there was a best order to introduce these models to students. Both were reluctant to change consensus models suggesting that they believed popular models were best or "right." On this issue, the teachers' views and the textbook's presentation of models are similar. As indicated previously, *Foundations of Chemistry* uses many models but only identifies five as models. This pattern is common in school chemistry textbooks and may account for the teachers' reluctance to volunteer models. It is recommended that secondary chemistry textbook authors pay more attention to the models and modelling processes on which chemistry depends.

The pattern of model use by biology teachers is more straightforward. On average, biology teachers volunteered seven models and these were evenly distributed between concrete or scale models and process models like feeding relationships and diffusion. When the data in Table 4 is scrutinised in more detail, *The Nature of Biology – Book 1* used almost equal numbers of concrete and scale models versus process models. *Senior Biology's* ratio of concrete and scale models to process models was about 3:2 and is explained by this books large number of diagrams modelling plant and animal structures.

Biology teachers were the most likely teachers to advocate simulations, role-plays and animations. This preference may be linked to popular video simulations of blood circulation, population growth and dinosaur programs. However, some of the biology teachers would not classify natural selection as a model and most denied that population simulations (video or student generated) were mathematical models. No teacher would accept that evolution was a theoretical model. Two biology teachers insisted that diagrams representing structures and processes were models. This has not previously been reported in the literature.

In agreement with van Driel and Verloop's (1999) study, the interviewed physics teachers used the most models and were the most creative. Yet physics textbooks contained the least models. This phenomenon may be related to the distribution and type of model used in physics textbooks. Very few concrete or scale models were found in *Physics One* and *Conceptual Physics.* Most of the models found in these textbooks were pedagogical analogical models in which an everyday action was analysed for its forces, motions and directions. An example is de Jong et al.'s (1990) explanation of how a vacuum flask minimises heat transfer (combined structural and process diagrams, p. 109). Many graphs and formulas also were used side-by-side (de Jong et al. used more formulas than Hewitt) but Hewitt used many cartoons to represent the processes involved in everyday actions. The form of representation may, therefore, have made the modelling process more transparent to physics teachers.

The teacher interviews and textbook analysis data suggests that there are links between the way textbooks use models and the way teachers teach with models. Still, further research is needed. The needed follow-up study should combine teacher interviews, teaching observations and textbook analysis. The detail needed precludes a large sample size and the interviews should include pre- and post-teaching discussions to compare teachers' intentions with their in-class actions.

Three more issues are now discussed in light of the interview and textbook data.

### *Imagination and Bridging Analogies*

When Steve shared his view of "what is a model?", he claimed that "students have fertile imaginations" and a "predictive capacity" that allows them to see connections between models and analogies: "you climb on a model ... [it] is like the telescope ... like a stepping stone." The stepping stone metaphor evokes Clement et al.'s (1989) 'bridging analogies' in which a carefully ordered set of analogies or models are used to bridge a conceptual gap that could not be spanned by one analogical model or verbal explanation. This thinking route suggests a theoretical framework for explaining why some sets of multiple models are highly effective (e.g., Clement's book on a table bridging analogy) while other are less effective (the sets of 4–5 molecular representations frequently used in chemistry textbooks, e.g., Parry, Dietz, Tellefsen, & Steiner, 1970, p. 41). Steve was the only teacher to express the belief that students are imaginative and creative and his attitude seems a fruitful way to introduce modelling and encourage students to take risks in their thinking and learning. The motivational literature reviewed by Pintrich et al. (1993) strongly supports his view.

The use of conceptually connected bridging models to develop a concept like balanced forces in 'the book on the table' instance agrees with Gentner's (1983) assertion that effective analogies are those that focus on deep process thinking rather than surface similarity. This also helps explain why sets of different molecular models confuse many students (Harrison & Treagust, 1996), especially students who are dualists. If the student is looking for one 'correct' model, models that look quite different are likely to confuse students if the conceptual links are not explained. With the exception of Keenan et al. (1980) and Zumdahl (1989), chemistry textbooks fail to explain these differences.

Cindy agreed with Gentner's claim that effective analogical learning occurs when the process concept is accessible to the student. Cindy said, "what I'm saying is the processes are the important part" and the "secret to success is to keep it very simple" and repeat the concept in a variety of contexts. Parallel models help students focus on the key concepts rather than the surface characteristics or 'noise' (Johnstone & Al-Naeme, 1991). Cindy's multiple models of the heart (and Jane's) are quite different – first four box chambers with vessels entering the top and leaving the bottom, similar diagram with all the vessels at the top, the same arrangement but with correct proportions added, then a plastic model and finally a sheep's heart dissection. The common concept in each model is the double circulation process – two 'ins' and two 'outs' for two circulation loops. The progression encourages students to search for the common theme rather than memorise factual information. Understanding of this type was seen in the student described by Harrison and Treagust (2000). In that study, Alex used five different models to explain how he visualised an organic compound's properties. Alex's multiple modelling outcome occurred in a typical Grade-11 chemistry class when multiple modelling of the type advocated by Cindy was practiced.

### *Patterns in Senior Science Textbooks*

A pattern is evident in Australian biology, chemistry and physics textbooks. Many textbooks published in the last 10–15 years cater for small audiences because they are written to satisfy single-state syllabuses in contrast to textbooks like *The Web of Life* (Australian Academy of Science, 1973) which was designed for national use. An apparent difference between wide-and-narrow audience textbooks is their breadth of coverage. Local syllabus textbooks consistently limit their content to the syllabus for which they were written. This limits the learning opportunities available to the students who read these books. The books can function as surrogate teachers but do they intellectually challenge and expand students' horizons? The scope and sequence in these textbooks means that teachers can be sure that the syllabus is covered by the book and that extraneous material will not waste the students' time; but does this ensure that our children become critical and scientifically literate citizens?

In the *Beyond 2000* report, Miller and Osborne (1998) recommend that "The science curriculum ... should be seen primarily as a course to enhance scientific literacy" (p. 4) and not a primer for university study. *Beyond 2000* and the current science education literature insist that we provide students with as wide a range of experiences as possible. These aims should encourage textbook writers to change their emphasis from content knowledge to process understandings and this includes elevating the status of modelling in the scientific enterprise.

### *Future Research Directions*

This research studied 10 biology, chemistry and physics teachers perceptions of the way they use analogical models to explain science to students. A strength of the interview approach was its ability to probe the teachers' recollections of how they think about and use models to teach science. Many of the responses were rich, reflective and raised important questions in the teachers' minds. Unexpected interview outcomes were some teachers' comments about how they saw science from a philosophical and/or an epistemological viewpoint. A weakness of the research was its inability to combine interview data with detailed observations of the teachers presenting models and responding to student comments and questions. Future research should comprise interviews with the teacher, observations of the teacher teaching and interviews with students. A study of this type was conducted in the mid-1990s but with one teacher (Harrison & Treagust, 2000, 2001). It seems essential that the next phace of this work study several teachers teaching model-rich curricula to typical classes.

Many open questions remain. Do teachers really use models the way they claim they do? How do teachers select the models that they use in class? How often do teachers and students negotiate the shared and unshared attributes of classroom models? Are teachers aware of the varied modelling abilities of their students? And, how can teachers effectively monitor students' understandings of teacher and textbook models? All these questions – and more – are interesting but there are tensions in research of this nature. One tension is the need to collect comprehensive data from many teachers using limited time and research resources. Another tension is knowing what happens in a classroom when it is not under scrutiny because the observation process affects the environment.

A useful way to address this lack of knowledge concerning the ways teachers think about and use models is the development of a sensitive and open-ended survey instrument. The patterns that emerge from this study and previous research (Harrison & Treagust, 1996, 1998, 2000, 2001) all suggest modelling questions that could be presented to teachers. Still, the broad-brush approach of a modelling survey should still be allied with actual observations of respondents teaching and talking about models with their students. Similarly, student perceptions should also be surveyed using a variant of the teacher instrument to compare and contrast students' and teachers' perceptions.

Researchers are making progress but important research still needs to be done. Scientific modelling is a fruitful area for both research and the professional education of teachers. The importance of these activities is heightened by the inclusion of *Science and Society* (including the nature of science) in new outcomes-based science syllabuses. Scientific literacy – which is manifest as the ability to think and work scientifically – is a substantial and expected outcome of school science. This paper has consistently argued and presented evidence showing that models and modelling are the main products of science, are an essential part of scientific methods, are important learning tools in science and are important teaching tools in science.

The interviews with teachers who claimed that they used few models and disagreed with one or more of these claims revealed that models were part of their thinking. However, they were unaware of how often and why they invoked and used models to explain scientific ideas. For these teachers, the interviews sensitised them to aspects of their pedagogy that they had previously ignored. It is likely that many science teachers fit this category; indeed, the data suggests that this may often be the case for chemistry teachers who accept with limited discussion the model-based flavour of their discipline. It is proposed that chemistry teachers may benefit most from modelling education that highlights the ubiquity of models in chemistry's theories, practices and explanations.

## Conclusion

This paper has argued that modelling is the essence of thinking and working scientifically. When ten teachers of Biology, Chemistry and Physics recounted their favourite explanations, analogies and models were prominent. Five findings emerge from the interview data. First, five teachers were aware that all analogical explanations break down somewhere and claimed that they discussed the limits of popular analogical models with their students. Second, the biology and physics teachers possessed extensive model repertoires and were comfortable that they could tailor analogical explanations to the needs of their students. Third, despite the frequent use of analogies and models in chemistry teaching, chemistry teachers seemed unaware that most of their syllabus content was communicated through models. Still, when key chemical models were raised in the interview, the chemistry teachers recognised and discussed the salient features of these models. Fourth, the large number of concept–process models that were volunteered is encouraging because these models develop conceptual rather than factual knowledge. Finally, the high-level thinking that is fostered by bridging analogies and models is very encouraging. The view that students have fertile imaginations and predictive capacities augers well for teaching and learning that promotes deep understanding in science.

The analysis of the ways school textbooks use analogical models to develop concepts is less encouraging. Few textbooks identify models as models and, apart from Kinnear and Martin (1992) and Hewitt (1992), the respective role and limitations of models are not discussed. In contrast, two popular college chemistry textbooks (Zumdahl, 1989; Keenan, Kleinfelter, & Wood, 1980) devote considerable effort to explaining modelling and the limits of analogies. It is curious that writers who cater for younger students assume that school students understand the methods and benefits of modelling. It is therefore recommended that Biology, Chemistry and Physics textbook writers encourage the use of effective analogies and models and highlight the shared and unshared attributes of the models they use to explain science concepts.

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## References

Anderton, J. (Ed.). (1983). *Fundamental physics.* Melbourne: Longman Cheshire.

Australian Academy of Science. (1973). *Biological science: The web of life.* Canberra: Australian Academy of Science.

Australian Academy of Science. (1990). *Biology, the common threads. Part 1.* Canberra: Australian Academy of Science.

Bent, H. (1984). Uses (and abuses) of models in teaching chemistry. *Journal of Chemical Education, 61*, 774–777.

Baker, J. J. W., & Allen, G. E. (1977). *The study of biology.* Menlo Park, CA: Addison-Wesley.

Black, M. (1962). *Models and metaphors*. Ithaca, NY: Cornell University Press.

Carr, M. (1984). Model confusion in chemistry. *Research in Science Education, 14,* 97–103.

Chalmers, A. (1999). *What is this thing called science?* Brisbane: University of Queensland Press.

Clement, J. (1987). Overcoming misconceptions in physics: The role of anchoring intuition and analogical validity. In J. Novak (Ed.), *Proceedings of the 2nd international seminar on misconceptions and educational strategies in science and mathematics* (Vol. III, pp. 84–97). Ithaca, NY: Cornell University.

Clement, J., Brown, D. E., & Zeitsman, A. (1989). Not all preconceptions are misconceptions: Finding ‘anchoring conceptions’ for grounding instruction on students’ intuition. *International Journal of Science Education, 11* (Special Issue), 554–565.

Cohen, L., Manion, L., & Morrison, K. (2000). *Research methods in education* (5th ed.). London: Routledge.

Coll, R. K. (1999). *Learners' mental models of chemical bonding.* Unpublished Ph.D. thesis, Curtin University of Technology, Perth, Western Australia.

Curtis, R. V., & Reigeluth, C. M. (1984). The use of analogies in written text. *Instructional Science, 13,* 99–117.

Dagher, Z. R. (1995). Analysis of analogies used by teachers. *Journal of Research in Science Teaching, 32*, 259–270.

De Jong, E., Armitage, F., Brown, M., Butler, P., & Hayes, J. (1990). *Physics one.* Melbourne: Heinemann.

DiSpezio, M. (1994). *Exploring living things.* Menlo Park, CA: Addison-Wesley.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75,* 649–672.

Duit, R., & Treagust, D. (1995). Teachers' conceptions and constructivist approaches. In B. J. Fraser, & H. J. Walberg (Eds.), *Improving science education* (pp. 46–69). Chicago: University of Chicago Press.

Dupin, J. J., & Johsua, S. (1989). Analogies and "modelling analogies" in teaching. Some examples in basic electricity. *Science Education, 73,* 207–224.

Feynman, R. P. (1994). *Six easy pieces.* Reading, MA: Helix Books.

Gabel, D., Briner, D., & Haines, D. (1992). Modelling with magnets. *The Science Teacher, 59*(3), 58–62.

Garnett, P. J. (Ed.). (1985). *Foundations of chemistry.* Melbourne: Longmans.

Garnett, P. J., & Treagust, D. F. (1992). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation reduction equations. *Journal of Research in Science Teaching, 29*, 121–142.

Gee, B. (1978). Models as a pedagogical tool: Can we learn from Maxwell? *Physics Education, 13,* 287–291.

Gentner, D. (1983). Structure mapping; Theoretical framework for analogy. *Cognitive Science, 7*, 155–70.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1–38.

Gilbert, J. K. (Ed.). (1993). *Models and modelling in science education*. Hatfield, Herts: Association for Science Education.

Gilbert, S. W. (1991). Model building and a definition of science. *Journal of Research in Science Teaching, 28,* 73–9.

Glynn, S. M. (1991). Explaining science concepts: A teaching-with-analogies model. In S. Glynn, R. Yeany, & B. Britton (Eds.), *The psychology of learning science* (pp. 219–240). Hillsdale, NJ: Erlbaum.

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799–822.

Halloun, I. (1996). Schematic modeling for meaningful learning of physics. *Journal of Research in Science Teaching, 33*, 1019–1041.

Harrison, A. G. (1994). Is there a scientific explanation for refraction of light? – A review of textbook analogies. *Australian Science Teachers Journal, 40*(2), 30–35.

Harrison, A. G. (1997). *Conceptual change in secondary chemistry: The role of multiple analogical models of atoms and molecules.* Unpublished Ph.D. thesis, Curtin University of Technology, Perth, Western Australia.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students mental models of atoms and molecules: Implications for teaching science. *Science Education, 80,* 509–534.

Harrison, A. G., & Treagust, D. F. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics, 98*(8), 420–430.

Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules and chemical bonds: A case-study of multiple model use in grade-11 chemistry. *Science Education, 84,* 352–381.

Harrison, A. G., & Treagust, D. F. (2001). Conceptual change using multiple interpretive perspectives: Two cases in secondary school chemistry. *Instructional Science, 29*, 45–85.

Hesse, M. B. (1963). *Models and analogies in science.* London: Seed and Ward.

Hewitt, P. G. (1992). *Conceptual physics.* Menlo Park, CA: Addison-Wesley Publishing Company, Inc.

Ingham, A. M., & Gilbert, J. K. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education, 13,* 193–202.

Johnstone, A. H., & Al-Naeme, F. F. (1991). Room for scientific thought. *International Journal of Science Education, 13,* 187–192.

Keenan, C. W., Kleinfelter, D. C., & Wood, J. H. (1980). *General college chemistry* ($6^{th}$ ed.). San Francisco: Harper and Row, Publishers.

Kinnear, J., & Martin, M. (1992). *Nature of biology: Book one.* Milton, Queensland: The Jacaranda Press.

King, R. J., & Sullivan, F. M. (1991). *Senior biology.* Sydney: Longmans.

Kline, M. (1985). *Mathematics and the search for knowledge*. New York: Oxford University Press.

Millar, R., & Osborne, J. (1998). *Beyond 2000.* London: Kings College.

Newton, T. J., & Joyce, A. P. (1990). *Human perspectives* ($2^{nd}$ ed). Sydney: McGraw-Hill.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner, & A. L. Stevens (Eds.), *Mental models* (pp. 7–14). Hillsdale, NJ: Erlbaum.

Osborne, R., & Freyberg, P. (1985). *Learning in Science: The implications of children's science.* Auckland, NZ: Heinemann.

Ogborn, J., Kress, G., Martins, & I, McGillicuddy, K. (1996). *Explaining science in the classroom.* Buckingham, UK: Open University Press.

Parry, R. W., Dietz, P. M., Tellefsen, R. L., & Steiner, L. E. (1970). *Chemistry: Experimental foundations* ($2^{nd}$ ed.). Englewood Cliffs, NJ: Prentice-Hall.

Patton, M. Q. (1990). *Qualitative evaluation and research methods.* Newbury Park, CA: Sage Publications.

Perry, W. G. (1970). *Forms of intellectual and ethical development in the college years*. New York: Holt, Rinehart and Winston.

Pimentel, G. C. (Ed.). (1963). *Chemistry: An experimental science.* San Francisco: W. H. Freeman & Co.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 197–199.

Queensland School Curriculum Council (QSCC). (1999). *Science Years 1 to 10 syllabus*. Brisbane: QSCC.

Sanchez, D., & Valcárcel, M. V. (1999). Science teachers' views and practices in planning for teaching. *Journal of Research in Science Teaching, 36*, 493–513.

Sutton, C. (1992). *Words, science and learning.* Buckingham, UK: Open University Press.

Tobin, A. J., & Dusheck, J. (1998). *Asking about life.* Fort Worth, TX: Saunders College Publishing.

Thiele, R. B., & Treagust, D. F. (1994). The nature and extent of analogies in secondary chemistry textbooks. *Instructional Science, 22,* 61–74.

Treagust, D. F., Duit, R., Joslin, P., & Lindauer, I. (1992). Science teachers use of analogies: Observations from classroom practice. *International Journal of Science Education, 14,* 413–422.

Treagust, D. F., Harrison, A. G., Venville, G., & Dagher, Z. (1996). Using an analogical teaching approach to engender conceptual change. *International Journal of Science Education, 18,* 213–229.

Treagust, D. F., Harrison, A. G., & Venville, G. (1998). Teaching science effectively with analogies: An approach for pre-service and in-service teacher education. *Journal of Science Teacher Education, 9*(1), 85–101.

Van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modelling in science. *International Journal of Science Education, 21,* 1141–1154.

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modelling method for high school physics instruction. *American Journal of Physics, 63,* 606–619.

Zumdahl, S. S. (1989). *Chemistry* (2nd ed.). Lexington, MA: D. C. Heath and Company.

Zook, K. B. (1991). Effect of analogical processes on learning and misrepresentation. *Educational Psychology Review, 3*(1), 41–72.