CHAPTER EIGHT

Interactions Between Analogical and Mental Models

Allan G Harrison

Abstract

Analogical reasoning is a common mode of communication but it is inconsistently used in school classrooms. Some teachers use analogies and models to explain science concepts while other teachers see them as two-edged swords. A better understanding of analogical reasoning is the aim of this research. Past research and current understandings are presented and the difficulties involved in accessing students' and teachers' mental models are discussed. The literature is analysed and a series of questions for future research proposed. In essence, the paper asks: can a rigorous method be found to effectively explore students' and teachers' evolving ideas during analogical model interactions? In other words, do deeply held knowledge, mental models and classroom experiences merge during analogical thinking; and in what ways is this interaction an amalgam of the social setting, the model itself and students' current and past ideas? Previous research suggest useful avenues to pursue and these are explored in the paper's discussion.

Introduction

The need to describe everyday phenomena in simple terms often recruits an analogy, model or similar device to explain complex ideas in simple terms. Analogies and models are popular because they help people visualise the objects and processes which they are trying to understand. Witness the use of analogies in social and sporting gathering or the back-of-an-envelope map to show a friend how to find his or her way to an important place. Maps and diagrams are very effective ways to describe and explain abstract ideas because they simplify or magnify the essential information. Despite its descriptive and explanatory popularity, however, analogy can be a two-edged sword (Duit, 1991; Glynn, 1991) because the meaning derived from an analogy by the hearer can agree with or be at odds with the meaning intended by the person presenting the analogy. School students find analogies particularly difficult to interpret and this paper tries to make some sense of analogical thinking in school classrooms.

The paper explores two specific questions: First, can researchers effectively study the meanings shared between teachers and students when analogies, metaphors or models are used to build understanding? This question is pertinent because constructivist theory insists that knowledge is a personal construct (Driver, 1995; von Glasersfeld, 1995) and Norman (1983) argues that the mental models people develop and access during learning are mostly inaccessible or unreliable. The second question concerns teachers' ideas about teaching with analogies and models: How do teachers decide when and where to use an analogy or model to explain a difficult idea to their students? Is this choice influenced by teachers' scientific and pedagogical knowledge (Harrison & Treagust, 2000a; Shulman, 1986) and do teachers take into account students' interests and knowledge when framing analogies and models? While the primary focus of each question is the personal construction of knowledge, the importance of the social context is recognised and discussed (Pintrich, Marx & Boyle, 1993; Strike & Posner, 1992; Vosniadou, 1994).

Models and Learning

Given their use in everyday conversation, it is not surprising that analogies are often used by teachers to explain concepts and objects to students (Dagher & Cossman, 1992; Feynman, 1992; Harrison & Treagust, 1993). The term analogy can refer to a specific story or parable, or be a superordinate heading for the set comprising analogies, metaphors and models. For instance, in the paper in which they discuss teachers' metaphors for a 'gene', Martins and Ogborn (1997) interchange the terms model and metaphor without explanation. In his extensive review, Duit (1991) also found that authors are inconsistent in the way they use the terms analogy and model.

Models provide an excellent way to highlight the key aspects of important ideas; particularly when the model strips away superfluous detail and draws the user's attention to the model's salient features. For example, Ogborn, Kress, Martins and McGillicuddy (1996) tell how a teacher used a piece of plastic hose to describe an earthworm—the plastic tube specifically modelled the earthworm's straight gut. Models also help learners by exaggerating the essential features of a process or an object; for example, the stick bonds and coloured spheres found in molecular models respectively model the bonding and the different elements. A third useful feature of an effective model is its accessibility to students because popular models are based on familiar objects and processes (Glynn, 1991).

Simplification, exaggeration and familiarity are all good reasons for using models in education, science and technology. Indeed, models come in all shapes and forms ranging from simple objects through to animations and simulations like virtual reality; for example, where do the models stop and the reality start in the film, *Jurassic Park*?

It is important to define the term "model" as it is used in this paper. All the models discussed from here on are analogical models and use a concrete structure, equation or graph, simulation or theory to describe and explain abstract ideas and non-observable entities. These models are analogical because they use a familiar object or experience to inform the learner about new and poorly understood objects, processes or concepts.

What is a Model?

The penchant for mechanical models in the nineteenth century was a distinctive feature of English science and technology and contrasted with the French desire for aesthetic and mathematical explanations (Hesse, 1963). Since that time, the suite of models used to explain everyday and scientific phenomena has grown to accommodate both the English and French views. Models can be classified along a conceptual continuum that begins with concrete scale models of plant and animal parts; extends through symbols, equations and graphs representing chemical reactions; and culminates in abstract mathematical and theoretical models like magnetic fields. To help make sense of this range, a typology of scientific models was proposed and is outlined in Figure 1. For details of the typology see Harrison and Treagust (1998, 2000a).

It is arguable that models—in their myriad forms—are thinking tools that are equally important in doing and learning science (Gilbert, 1993; Grosslight, Unger, Jay &

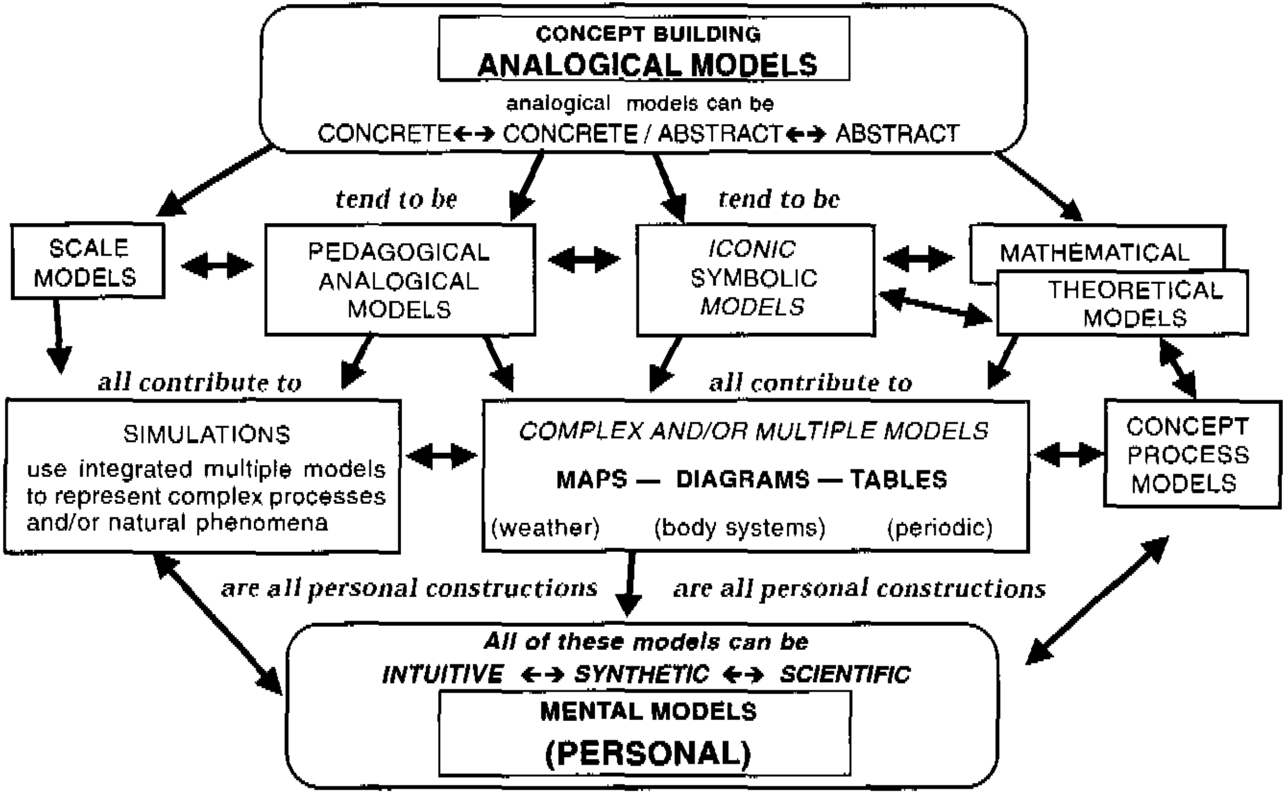

Figure 1: *The model typology used in this paper (Harrison & Treagust, 1998)*

Smith, 1991). In particular, Gilbert argues that models are important products and methods of science and that models are major teaching and learning tools in science. However, when Grosslight et al. compared the ways Grade 7 and 11 students and experts used models, they found important differences. They classified lower secondary students as naïve modellers because these students believed that a 1:1 correspondence existed between models and reality, that models are 'right'; and there is no systematic purpose embedded in a model's form. More experienced students were likely to accept and use alternative models but experts alone understood that models should be multiple; are mental tools, and can be manipulated by the modeller to suit his/her thinking needs. From this perspective, modelling is a high level thinking tool and should be an explicit part of scientific literacy.

This leads to the question of what is a model? and, how is a model a thinking tool? Much of what we know about models and modelling comes from modelling's analogical origin and for this reason, the models that are constructed and used to represent objects, processes and relationships are called 'analogical models'. Analogical models are believed to function in the same way as an analogy (Duit, 1991; Gentner, 1983) and models are believed to be heuristic when they highlight ways in which a familiar object or process is like an unfamiliar object or process. A popular biology textbook describes models this way:

> A model is a simplified picture or representation of an 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. (Kinnear & Martin, 1993, p.10)

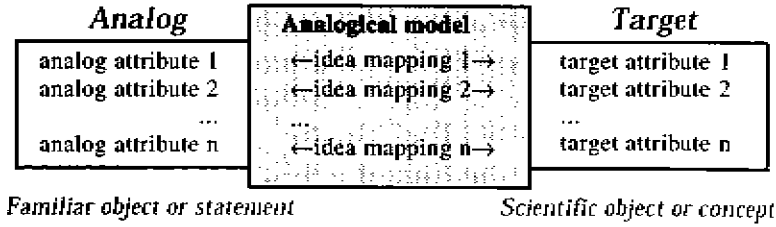

Figure2: Analogical transfer of ideas from a familiar analog to a scientific target

A 'model' of an analogical model is presented in Figure 2. The model is shown as a set of relations that connect the *analog* (the familiar object or process) to the *target* (the unfamiliar scientific object or process). The shaded overlap is intentional and suggests that the *analog* is mentally connected to the *target* through the agency of the analogical mappings. Analogical mappings come in two forms: structural similarity and shared relationships. For example, a chair is like a table because it has four legs; however, this similarity does not permit one to sit on the table (well, not in 'good' company). Likewise, two objects have no more than a random chance of having the same function if size is the basis of their similarity. In contrast, "common relations are essential to analogy" (Gentner & Markman, 1997, p.46) and common relations are an acceptable ground for transferring meaning from the analog to the target. Insistence that analogy and modelling depends on relational mappings is evident in Gentner and Markman's example of how Kepler used analogy to derive his laws of planetary motion. Relational analogy is also foremost in Hewitt's (1992) model for the refraction of light—refracting light is like a pair of wheels that change direction as they obliquely roll from a hard to a soft surface (p.437). In Figure 3, the wheels slow down and change direction as they cross the hard-soft interface and light similarly slows down and changes direction when it passes from air to glass. The potential of the wheels analogy to successfully foster and sustain conceptual change in Grade-10 students was researched and reported by Treagust, Harrison, Venville and Dagher (1996). One class of girls was taught refraction

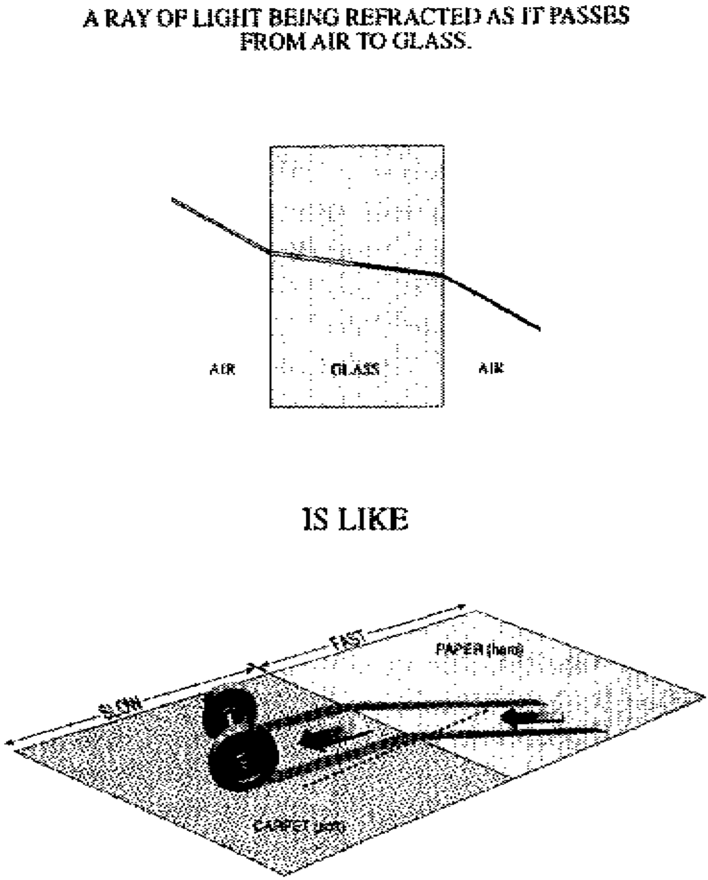

Figure 3: *A pair of wheels rolling form a hard to a soft surface change direction like a ray of light passing from air into glass.*

using the analogy and a similar class was taught refraction without the analogy. Based on prior learning and assessments, the classes were believed to be of equal ability. After three months, however, no student in the no-analogy class could explain refraction while 36% of the analogy class were adjudged to hold a fruitful conception and another 28% held a plausible conception of refraction (Hewson & Hewson, 1992).

Analogical Models and the Personal Construction of Knowledge

Current understandings of how analogical transfer takes place insist that only the person exploring the similarities and differences between the *analog* and the *target* can decide what is 'like' and what is 'unlike'. Other participants—teachers and peers—can suggest relationships between the analog and the target but it is the learner's personal decision whether or not an analogy and its mappings are intelligible, plausible or fruitful (Hewson & Hewson, 1992). This heuristic view of modelling as a high-level thinking task articulates with Gilbert's view that modelling is an important aspect of the scientific method, a significant product of science, and an important way to teach and learn science. This harmonises with Gentner's view that analogy is much more than similarity; and a learner benefits most when "not just shared *relations* but shared *higher-order relations*" are recognised and understood (italics in original, Gentner, 1988, p.76). In the same paper, Gentner argues that systematically related mappings are much more effective in achieving analogical transfer—that is, learning about the target—than isolated or single mappings (called simple analogy by Curtis & Reigeluth, 1984). When the student recognises a shared relation, s/he usually looks for more shared ideas, but models sharing multiple relationships are rare. This creates a problem for students trying to interpret analogies—they often see and believe relations that are not valid. This is why Glynn called analogies two-edged swords. A well-known analogy or mathematical model that does share multiple relations is the attractive force between two charged objects (e_1 and e_2) and the force of gravity between two masses (m_1 and m_2). The analogy is evident when the two mathematical models are compared:

Electric force $F \propto \frac{e_1 e_2}{r^2}$ is analogous to gravitational force $F \propto \frac{m_1 m_2}{r^2}$

Analogical Models and Learning

The learning power of a model lies in its capacity to suggest new ways to think about old ideas. Models are thinking tools because the modeller compares and contrasts the new model with ideas already present in his or her mind. Most models are social constructions; that is, at least two people are sharing information but only the hearer can decide how s/he is going to interpret the analogy or model. Seen in this light, analogical interpretation involves the personal construction of meaning (von Glasersfeld, 1995). Constructivism is an epistemology; that is, it is a theory of knowledge that has major implications for the way we teach and learn. While partly true of constructivism, it is over-simplistic to say that new knowledge is just a product of what the student already knows and his or her current experiences. Posner, Strike, Hewson and Gertzog (1982) and Strike and Posner (1985) used Toulmin's (1970) notion of conceptual ecology to make sense of what happens during learning. Conceptual ecology is a useful metaphor for the set of explicit and implicit assumptions held by the learner and Figure 4 summarises some components of an active conceptual ecology. It is likely that in a class of 20-30 students, many permutations of these factors or conceptual ecologies will exist. This further complicates the way students learn from analogies, metaphors and models presented by teachers and textbooks.

When learning occurs through the agency of analogies and models, the constructed meaning is an interaction product between the analogical experience and some or all of the items in the student's conceptual ecology. Based on Figure 4, many commitments, interests and knowledge items may influence analogical transfer. Analogical reasoning can be called "meaningful learning" of the type espoused by Ausubel (1968) and described by Novak (1984, p. 608) because "the learner must make a conscious effort to relate new knowledge to knowledge he or she already has" and the new knowledge is both "non-arbitrary and substantive". In this sense, the 'rightness' of a model is relatively unimportant because all models break down somewhere. If a person thinks that a specific model is 'right', s/he is unlikely to explore new ways in which the analog might be like (or unlike) the object or concept to which it is

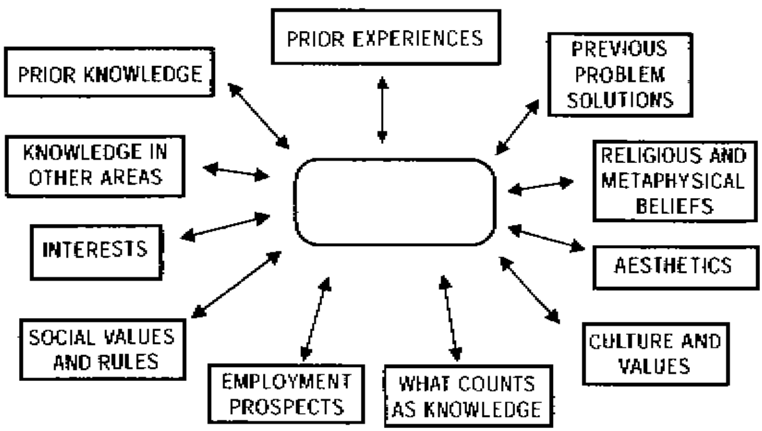

Figure 4: *Some of the more common components of a student's conceptual ecology.*

being related. Deeming a model to be right is likely to hinder meaningful learning whereas suspending judgment on a model should enhance learning. Put another way, analogies, metaphors and models are valued for their ability to open-up thinking not for their ability to establish 'truth'.

Researching Modelling

This raises a problem with studying modelling. If the hearer controls the meaning-making, how can a teacher understand what a student is thinking when a model is used in class? This issue also is problematic for the researcher who tries to make sense of analogical modelling in school and is a variation on the emic—etic problem troubling some interpretive researchers (Cohen, Manion & Morrison, 2000). How can the outsider—the teacher or the researcher—understand what is going on in the insider's world when that world is wholly contained in the student's mind? Norman's (1983) warning is especially important—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 accurate, but they must be functional. Norman cautions 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 derived from interviews and learning discussions are no more than the investigators' interpretations (Duit & Treagust, 1995). Several contributors to *Mental models* (Gentner & Stevens, 1983) used the construct "mental model" to describe student understandings and this term was used extensively by Vosniadou (1994) to describe her interpretations of children's conceptions. There is then, a need to distinguish between the models *accepted* by the knower (which are inaccessible) and the stated mental models that purport to represent what people think and do (e.g., interview responses, demonstrations, written work and examination answers) because these differences will influence research interpretations.

Vosniadou (1994) points out "that the mental models individuals generate or retrieve during cognitive functioning are the points at which new information is incorporated into the knowledge base" (p. 48). The mental models employed by a learner are likely indicators of his or her ontological and epistemological framework presuppositions and the mental models may act as conduits to and from the underlying framework theory. This psychological model depicts framework theories as the robust understandings that a person has about themselves and the world and are analogous to Lakatos' (1970) "hard core" knowledge. In contrast, mental models resemble the fluid schemata or the "protective belt" knowledge that changes during learning. In Lakatos' theory of how scientific ideas evolve in communities, strongly held "hard core" concepts are surrounded by a "protective belt" of changeable knowledge items. In this model, people modify knowledge items in the protective belt to protect their deeply held commitments from falsification. This helps explain why conceptual change is so difficult to achieve with respect to strongly held alternative conceptions and frameworks (Tyson, Venville, Harrison & Treagust, 1997).

Researchers often claim that information gained about student mental models elucidates some of the features of the underlying framework theory. If the above model fairly represents mental models as intermediary understandings between external experience and deeply held knowledge, then mental models are probably unreliable indicators of core conceptions. For instance, the ideas that a learner is manipulating in his or her volunteered mental model may agree or disagree with his or her core conceptions. Students, in particular, are adept at telling teachers what they think the teacher wants to hear. This raises the question of whether Vosniadou's and Norman's mental models are similar or different. Vosniadou paints an interesting scenario when she proposes that mental models are a conduit between deep understandings and the things a person says and does. Are mental models a hybrid between the social interaction (what is seen and documented) and the individual learner's innermost thoughts? Are mental models knowledge in development that are restricted to the protective belt, or do they impinge on and reveal facets of core knowledge?

Norman (1983) argues that a target concept is most fully represented in the scientists' conceptualisation of the target or scientific concept. The scientists' conceptualisation is the agreed understanding of the community of science experts and may change over time in response to new evidence or new theories. Indeed, most scientists have sets of multiple conceptual models and the model they use in a particular situation is usually context dependent. Practitioners who apply this knowledge, for example teachers, attempt to create conceptual models that are appropriate to the age of their students and the published curriculum (Shulman, 1987). A conceptual model created by the teacher is thus a version of the scientists' model, and will be less detailed and more idiosyncratic than the scientists' conceptualisation. This teacher version could be called the teacher's mental model. The teacher presents his or her mental model to the students and the students construct their mental model of the teachers' version of the scientists' conceptualisation. Such repeated iterations mean that the students' mental model will likely differ from the scientists' model because the student's mental model is not the teacher's version, rather, it is a hybrid of the teacher's conceptual model and the student's conceptual ecology. It is for these reasons that this research is interested in the ways teachers and students use models to teach and learn from models.

Both Strike and Posner (1992) and Vosniadou (1994) believe that such teacher-student interactions account for many of the misconceptions that emerge during teaching. Research has very effectively described the misconceptions but is particularly ineffective in explaining how the misconceptions evolve. One reason for limited research is the elusive nature of mental models and this complicates our understanding of conceptual learning. This should not deter us; rather, it should encourage us to develop credible ways to explore and explain conceptual learning.

This brings the discussion back to modelling because modelling involves deep relational learning. The notion that learning using analogies and models is straightforward is difficult to sustain, especially when the model is not carefully discussed nor is the point where the model breaks down identified. Analogical models are effective learning tools provided the analog is familiar and the shared and unshared mappings are understood by the teacher and the students. Teachers are more likely to negotiate models with their students today than 10 years ago and this is a positive step (compare Treagust, Duit, Lindauer & Joslin, 1992 with Harrison, in press).

The last point to consider is the finding reported by Zook (1991). He showed that students find it difficult to generate their own models but once they have constructed their model, they map it quite easily. Conversely, students easily accept teachers' models but find teachers' models hard to map! That students have difficulty generating analogies and models is implied by the absence of student-generated analogies and models in the literature. Apart from Cosgrove (1995) and Wong (1993), student generated analogies and models are rarely reported.

The Author's Previous Research

The current interest in students' evolving mental models and teachers' perceptions of how and when to use scientific modelling is the fourth phase of a project that began in 1994. First, Grade 8-10 student understandings of atomic and molecular models were surveyed to expand our insights into the ways students interpret scientific models (Harrison & Treagust, 1996). Second, a typology of school science models was developed using the literature, previous and current research (Harrison & Treagust, 1998) and 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, 2000b, in press). The studies turned up new ways that students interpret models like electron clouds and electron shells and the study findings reinforced key assertions made by Norman (1983), Strike and Posner (1992) and Vosniadou (1994). For instance, some students use models in predictable ways, yet others in the same class react in different and inconsistent ways to modelling experiences. Two equally capable Grade-11 students illustrate the point: Alex became a multiple modeller for whom models were creative thinking tools. In contrast, his friend Dan presented rich but internally contradictory evidence about his modelling beliefs (Harrison & Treagust, 2000b, in press).

Having studied student modelling in detail, it was timely for me to ask, How do teachers think about the models they use to represent scientific objects and processes? Do variations in teacher beliefs contribute to students' inconsistent use of models as thinking tools? Indeed, how do models and a teacher's mental model interact during teaching and, how do models interact with student's mental models during learning? Are these interactions independent or interactive?

As a first step, experienced teachers' 'think aloud' talk about models was studied during ten open-ended interviews. Interview is a useful way to start exploring teachers' perceptions of their practice and the interviews were designed to be comprehensive and flexible. Four teachers came from one school and six from another school and all were science graduates with science teaching qualifications. The interviewees' had been teaching for 6-25 years with a median of 10 years. All 10 teachers taught middle school science and at least one senior subject—Biology, Chemistry, Physics or Senior Science. A phenomenological approach was used to make sense of the modelling ideas discussed in the interviews (Cohen, Manion & Morrison, 2000). Data were derived from the transcripts, classified and reported in tables and vignettes (see Harrison, in press).

The Interviews

First, each teacher was asked about his/her academic qualifications, teaching experience, classes taught, and main science teaching interest. Then 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 question aimed to elicit the favourite, analogies, metaphors or models used by individual teachers when an alternative explanation was needed. The probe was quite successful with poppet bead models of genes and chromosomes emerging on three occasions (biology teachers) plus a detailed analogy of photosynthesis from a physics teachers. Next, each teacher was shown a set of five analogical models and asked to comment on a scale model heart; a model boat; a text-book diagram of diffusion; five representations of ammonia, and a simple tube for an earthworm's gut (Ogborn et al., 1996).

Each teacher also was quizzed on John Gilbert's (1993) four assertions about models.

> *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 interview then explored each teacher's ideas about the 'fixedness' of consensus models and whether common models can be modified by the teacher or the students to accommodate student learning needs. The interviewer also asked if the teacher discussed the shared and unshared attributes of models with his/her students and whether s/he encouraged students to construct their own models.

Data, Interpretations and Findings

For this paper, sample teacher perceptions are offered to illustrate the richness of teacher thinking about models. These excerpts provide some reasons why further research into the ways teachers' and students' mental models interact with analogical models is worthwhile. It is recognised that such research can be difficult; however, a rigorous study seems worth attempting. Some samples:

> *Students have fertile imaginations ... we have 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 is maybe like the telescope 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 area and knowing well [what is] in the known area ... you know unknown aspects of the new area.*
>
> *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. (Steve, a physics teacher)*
>
> *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. (Karen, a biology and physics teacher)*
>
> *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. (Cindy, a biology teacher)*

Steve's stepping-stone effect is a feature of 'bridging analogies' which are a fruitful way to maximise the effect of multiple analogical models (Clement, Brown & Zeitsman, 1989). Cindy's "prop" may also serve a similar function; she then expressed a preference for using animations to explain non-observable science processes like diffusion, sound and hearing, and cellular transport.

The way Cindy uses them, animations are stripped of all unnecessary information:

> *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.*

A summary of the ten teachers' comments yielded a suite of model attributes. Three teachers believed that models are *simplifications* (Cindy, Ian and Steve) while David saw them as *proportionally distorted* and Karen liked *enlarged or exaggerated* models (Ogborn et al., 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 et al., 1991), Cindy prefers multiple models (Harrison & Treagust, 2000b) and Ian feels that effective models are *personal constructions.*

The links to the literature indicate that these all are desirable features of models and analogies and these links provide a productive avenue for further research.

Gilbert's Propositions and Modelling Level

When John Gilbert's (1993) claims about the value of models in science were discussed, all 10 teachers agreed that models are major *tools* of science. However, three teachers disagreed or held reservations about models being the main *products* of science, 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. Gilbert's propositions are 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. The fourth finding—not all agreed that models are important teaching tools—is particularly interesting and worthy of detailed investigation.

Models and their Limitations

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). Steve had most to say about shared-unshared model attributes 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. Neither of the chemistry teachers performed this task while about half the biology and all the physics teachers did so. The chemistry teachers' views are especially curious given the large number of models that are used to explain chemical phenomena.

Model Repertoires and Teaching Domain

Eight of the 10 teachers volunteered an extensive range of models with the greatest range coming from the biology teachers. The biology teachers offered an average of seven models each. The three physics teachers: David (11 models), Steve (6 detailed models in the longest transcript) and Karen (10 models) used the greatest number of models and two of them used models across subject areas. Surprisingly, the two teachers who volunteered the fewest models—just one model each—were chemistry teachers and these two teachers asserted that models are not important teaching tools. 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. Both chemistry teachers agreed that the use of multiple models is desirable but were unwilling to manipulate models—"you cannot modify accepted models" (Colin); and, "this is the model that all students should learn" (Hans). It may be that chemistry teachers perceive chemistry models as a form of reality. 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 the teachers' repertoires also means that their students are exposed to descriptive and thinking models. Two very encouraging aspects of the data are the preference shown by four teachers for simulations and role play models, and the fact that five of the teachers regularly explain to students where each model breaks down. Collectively, the views of the 10 teachers at the two schools comprise a rich, comprehensive and creative view of modelling. While the teachers' collective model use satisfies almost all the literature's recommendations for effective model use; only two teachers individually met Grosslight et al.'s expert modeller criteria.

Discussion and Conclusions

Imagination and Bridging Analogies

Steve 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 is 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). 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 use of conceptually connected 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. 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. Cindy's multiple models of the heart resembles the book-on-the-table approach. First she uses four box chambers with vessels entering the top and leaving the bottom; second, she uses a similar diagram with all the vessels at the top; third, the same arrangement but with correct proportions added; fourth, a plastic model is examined and finally a sheep heart is dissected. The common concept in each model is the double circulation process—two 'ins' and two 'outs' for two circulation loops. A model progression like this encourages students to search for the common theme rather than memorise factual information. It is important that research identify, document and communicate these effective multiple models (Harrison & Treagust, 2000b).

Future Research Directions

A strength of this interview study was its ability to probe the teachers' recollections of how they thought about and used 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 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, 2000b; Harrison & Treagust, in press). It seems essential that the next phase 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? 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 may be the development of a sensitive and open-ended survey instrument. The patterns that emerge from this study and previous research (Harrison & Treagust, 1996; 1998; in 2000b; in press) all suggest modelling questions that could be presented to teachers. Still, the broad-brush approach of a modelling survey should be allied with observations of respondents teaching and talking about models with their students.

Researchers are making progress but important research remains 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. What is needed is information informing our understanding of how teachers, students, and analogical models interact during learning.

References

Ausubel, D. P. (1968). *Educational Psychology: a Cognitive View.* New York: Holt, Rinehart and Winston.

Chalmers, A. (1999). *What is this Thing Called Science?* University of Queensland Press: Brisbane.

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.

Cosgrove, M. (1995). A Case Study of Science-in-the-Making as Students Generate an Analogy for Electricity. *International Journal of Science Education, 17, 295-310.*

Curtis, R. V., & Reigeluth, C. M. (1984). The Use of Analogies in Written Text. *Instructional Science, 13,* 99-117.

Dagher, Z. & Cossman, G. (1992). Verbal Explanations Given by Science Teachers: Their Nature and Implications *Journal of Research in Science Teaching, 29,* 361-374.

Driver, R. (1995). Constructivist Approaches to Science Teaching. In L. P. Steffe, and J. Gale, *Constructivism in education (pp. 385-400).* Hillsdale, NJ: Erlbaum.

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.

Gentner, D. (1983). Structure Mapping: Theoretical Framework for Analogy. *Cognitive Science, 7,* 155-70.

Gentner, D. (1988). Analogical Transfer and Analogical Access. In A. Prieditis (Ed.), *Analogica* (pp. 63-88). Los Altos, CA: Morgan Kaufmann Publishers.

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 and 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.

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. (in press). How do Teachers and Textbook Writers Model Scientific Ideas for Students? *Research in Science Education.*

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. (1994). Science Analogies. *The Science Teacher, 61* (4), 40-43.

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. (2000a). A Typology of School Science Models. *International Journal of Science Education, 22,* 1011-1026.

Harrison, A.G., & Treagust, D.F. (2000b) 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. (in press) Conceptual Change Using Multiple Interpretive Perspectives: Two Cases in Secondary School Chemistry. *Instructional Science*.

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.

Hewson, P. W., & Hewson, M. G. A B. (1992). The Status of Students Conceptions. In R. Duit, F. Goldberg, & H. Niedderer. (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies* (pp. 59-73). Proceedings of an International Workshop. Kiel, Germany: Institute for Science Education.

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

Lakatos, I. (1970). Falsification and the Methodology of Scientific Research Programmes. In I. Lakatos & A Musgrave (Eds.), *Criticism and the Growth Of knowledge*. Cambridge: Cambridge University Press.

Martins, I., & Ogborn, J. (1997). Metaphorical Reasoning about Genetics. *International Journal of Science Education, 19*(1), 47-62.

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

Novak, J. (1984). Application of Advances in Learning Theory and the Philosophy of Science to the Improvement of Chemistry Teaching. *Journal of Chemical Education, 61*, 607-612.

Ogborn, J., Kress, G. Martins, I, McGillicuddy, K. (1996). *Explaining Science in the Classroom*. Buckingham: Open University Press.

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.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change. *Science Education, 66*, 211-227.

Shulman, L. (1986). Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher*, 15(2), 4-14.

Strike, K.A., & Posner, G.J. (1992). A Revisionist Theory of Conceptual Change. In R..A. Duschl & R. .J. Hamilton (eds.), *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice* (pp. 147-176). New York: State University of New York Press.

Toulmin, S. (1972). *Human Understanding: Vol. I*. Oxford: Oxford University Press.

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*, 4, 413-422.

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.

Tyson, L.M., Venville, G.J., Harrison, A.G., & Treagust, D.F. (1997). A multi-Dimensional Framework for Interpreting Conceptual Change Events in the Classroom. *Science Education,81*,387-404.

von Glasersfeld, E. (1995). Sensory Experience, Abstraction and Teaching. In L. P. Steffe, and J. Gale, *Constructivism in Education (pp. 385-400)*. Hillsdale, NJ: Erlbaum.

Vosniadou, S. (1994). Capturing and Modelling the Process of Conceptual Change. *Learning and Instruction, 4*, 45-69.

Wong, E. D. (1993). Self Generated Analogies as a Tool for constructing and Evaluating Explanations of Scientific Phenomena. *Journal of Research in Science Teaching, 30*, 367-380.

Zook, K. B. (1991). Effect of Analogical Processes on Learning and Misrepresentation. *Educational Psychology Review, 3*, 1, 41-