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A typology of school science models

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Modelling is the essence of thinking and working scientifically. But how do secondary students view science models? Usually as toys or miniatures of real-life objects with few students actually understanding why scientists use multiple models to explain concepts. A conceptual typology of models is presented and explained to help teachers select models that are appropriate to the conceptual ability of their students. The article concludes by recommending that teachers model scientific modelling to their students, encourage the use of multiple models in science lessons, progressively introduce sophisticated models, systematically present in-class models using the Focus, Action and Reflection (FAR) guide and socially negotiate all model meanings.

Introduction

When you last visited an art gallery what impressed you most: the pictures' and sculptures' literal realism or how you interpreted them? When you next read a book like *The language of the genes* (Jones 1993) or *The periodic kingdom* (Atkins 1995) how will you interpret the models used by the authors? Why are charts of the solar system and plant life cycles, model hearts and electric motors, models of molecules and cells, equations, graphs and computer simulations so popular in classrooms? And who would think of building a house or boat without drawing plans or making a scale model? All these models and pictures exist because imaginative people enrich their work and leisure with artistic, educational and technological devices.

Many science curricula now promote investigating, understanding and communicating as the essence of *thinking and working scientifically* (e.g. Queensland School Curriculum Council 1999). Models are integral to thinking and working scientifically and it can be argued that science and its explanatory models are inseparable because models are science's products, methods and its major learning and teaching tools (Gilbert 1993, pp. 9-10). Sutton (1992) supports this interdependence when he says that:

> I see all modelling as inspired by some associated imagery, which can in part be explored verbally. Models, like the metaphors on which I argue they are based, carry entailments or implications, and so they quickly yield the testable predictions that all scientists want. (p. 98)

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Models and scientific discovery

Science stories like those about Kepler, Huygens and Maxwell support the view that mental imagery, experimentation, theorizing and communication are inseparable. More recently the unlocking of DNA's double helix was a very human experience replete with all the frustrations and exhilirations of trying to make sense of tenuous data. Watson and Crick reached a point where they had to make models. They had mental images and suspicions about DNA's structure but Watson claims that their success rested on model building. This is how he remembers their triumph:

> The brightly shining metal plates [purines and pyrimidines] were then immediately used to make a model in which for the first time all the DNA components were present. In about an hour I had arranged the atoms in positions which satisfied both the X-ray data and the laws of stereochemistry. The resulting helix was right-handed with the chains running in opposite directions. (Watson 1968, p. 158)

Indeed, Watson insists that it was the model of DNA that convinced opponents of heuristic modelling that 'model building represented a serious approach to science, not the easy resort of slackers who wanted to avoid the hard work necessitated by an honest scientific career' (p. 166).

Science education shares this interest in models and modelling. While many scientific phenomena cannot be reproduced in the classroom because of time and safety constraints, models of these objects and processes are available. Models are accessible and teachers know that students enjoy playing with them (Harrison 1996) and that modelling is an important constructivist teaching strategy. It is, therefore, important to explore the ways students construct, manipulate, and interpret the scientific models in school science lessons.

Models: thinking and working scientifically

Over the past 30 years, modelling has been researched from the philosophy of science (Black 1962, Hesse 1963), epistemology (Gilbert 1993, Grosslight *et al.* 1991), explanations (Gilbert *et al.* 1998a, 1998b) and classroom practice (Hodgson 1995, Wells *et al.* 1995, Halloun 1996, Harrison and Treagust 1996). The prime interest of this paper is the analogical models that teachers and textbooks use to represent science knowledge. Analogical models comprise the scaled and exaggerated objects; symbols, equations and graphs; diagrams and maps; and simulations that facilitate scientific communication. They can be concrete, abstract or theoretical depending on the needs of their author and audience, but above all models must enhance investigation, understanding and communication and this makes them key tools in thinking and working scientifically.

This article claims that model-based thinking is a sophisticated process that should be an explicit part of learning in science. It argues that teachers should be sensitive to the familiarity of, and similarities and differences between the models they use to explain science phenomena. The scope and application of analogical models in thinking and working scientifically seems limited only by the modeller's purpose and creativity and while this article cannot survey every model and application, it proposes a model classification with examples, presents a systematic strategy for teaching with models in school science, and identifies questions for future research.

Modelling in school science lessons

Science students often are poorer modellers than teachers expect and secondary students usually do not look further than a model's surface similarities. Grosslight *et al.* (1991) studied student - expert modelling in terms of students' 'beliefs' about the structure and purpose of models. They classified many lower secondary students as level 1 modellers because these students believe that there is a 1:1 correspondence between models and reality (models are toys or small incomplete copies of actual objects); models should be 'right', and they do not search the model's form for ideas or purposes. Some secondary students achieve level 2 where models remain real world objects or events rather than representations of ideas; and the model's main purpose is communication rather than for exploring ideas. Experts alone satisfy level 3 criteria that models should be multiple; are thinking tools; and can be purposefully manipulated by the modeller to suit his/her epistemological needs. Some students fell into mixed level 1/2 and 2/3 classifications.

This suggests that many science students view models as reality and that student modelling is more algorithmic than relational. This means that many students look for the best fit or 'right' model so that they can memorise its details, meaning and applications, and reproduce the 'facts' in tests. An example is the 'shell' model for the arrangement of electrons in atoms (e.g. Jones *et al.* 1993, Tobin 1994). Secondary chemistry students preferentially use this diagram to explain atomic structure, valence and bonding (Harrison and Treagust 2000) and it is rare for students to use electron clouds or multiple models to explain atomic properties. Even when students do use sophisticated atomic models; the idea that the model is 'right' and 'real' persists (Sandomir *et al.* 1993, Harrison and Treagust 1996).

Teaching built around Grosslight *et al.*'s (1991) modelling levels and Perry's (1970) intellectual positions showed that students can learn to think and work scientifically with models provided their interests and prior knowledge are accommodated. Research in secondary science classes claims that students can learn to think of multiple models for a phenomenon as complementary and can think in more sophisticated ways than was previously accepted (Harrison and Treagust 2000). A useful finding was that Grade-11 chemistry students who became creative multiple modellers realized that no model was wholly right and began to see science as more about process thinking than object descriptions.

Other studies suggest that school students and some teachers think about science models in mechanical terms and believe that 'scientists know the answers' (Gilbert 1991, Abell and Roth 1995). But models are not 'right answers', rather, they are the methods and the products of science and it is quite impossible to teach and learn science without using models. How can we describe or explain atoms, genes, chemical reactions or continental drift without using one or more models? Teachers consistently use models to explain immaterial processes like equilibrium (e.g. a balanced seesaw) and non-observable entities like electrons flowing in a wire (e.g. a water circuit). Can students understand the carbon cycle, blood circulation or chemical families without diagrammatic models? And what do teachers do when they see the worried looks on their students' faces in the middle of an abstract explanation? They reach for an analogy or a model and this may explain the frequent use of analogical models in science lessons.

Still, it is curious that many teachers are wary of verbal analogies (Glynn 1991), do not often use them (Treagust *et al.* 1992) and yet employ physical models, diagrams and iconic symbols on a daily basis. Perhaps teachers are conscious of the unreliable way that students interpret spoken analogies because of their verbal format and the need for students to construct a mental image of the situation under discussion. In contrast, the common occurrence of models in textbooks, in classroom displays and as lesson 'motivators' evidences teachers' and curriculum writers' willingness to use models. The more frequent use of models than analogies suggests that teachers are less aware or less critical of model ambiguity. The concrete form of many models may, in fact, desensitise teachers and writers to the insecurity felt by students when faced with oversimplified or multiple models (Bent 1984, Carr 1984).

For this reason, data collected from classroom observations and interviews (Harrison, 1996) and the education and science literature were used to frame a classification or typology of analogical models. A 'model' of the typology is presented in figure 1 and is explained under the subsequent headings. The classification attempts to characterize the similarities and differences evident in the teaching and learning models that are used in science lessons.

A likely benefit of the typology is that it will alert teachers and writers to the conceptual demands of the different model types. Models differ widely in the demands they place on students. Much research agrees that students' model interpretations inconsistently match the teacher's intentions (Garnett and Treagust 1992a, 1992b, Carr 1984; Harrison and Treagust 1996). Furthermore, knowing that a student successfully interprets a concrete scale model does not mean that s/he can interpret a mathematical, theoretical, or concept-process model. It is important that teachers carefully assess the conceptual demands that their teaching models place on their students and carefully negotiate each model with their students.

A classification of analogical models

Scientific and teaching models

1. Scale models

Scale models of animals, plants, cars, boats and buildings are used to depict colours, external shape and structure. Scale models carefully reflect external proportions but rarely show internal structure, 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 1987, pp. 259-263). Scale models are often toys or toy-like (Grosslight *et al.* 1991) and this realism may obscure the unshared model - target differences.

2. Pedagogical *analogical* models

This category subsumes all the analogical models used in teaching and learning and includes scale models. They are called 'analogical' because the model shares information with the target (Glynn 1991) and 'pedagogical' because they are teacher crafted explanations that make non-observable entities like atoms and molecules accessible to students (Shulman 1986). One or more attributes dominate the analogue's structure; for instance, balls and sticks in molecular models

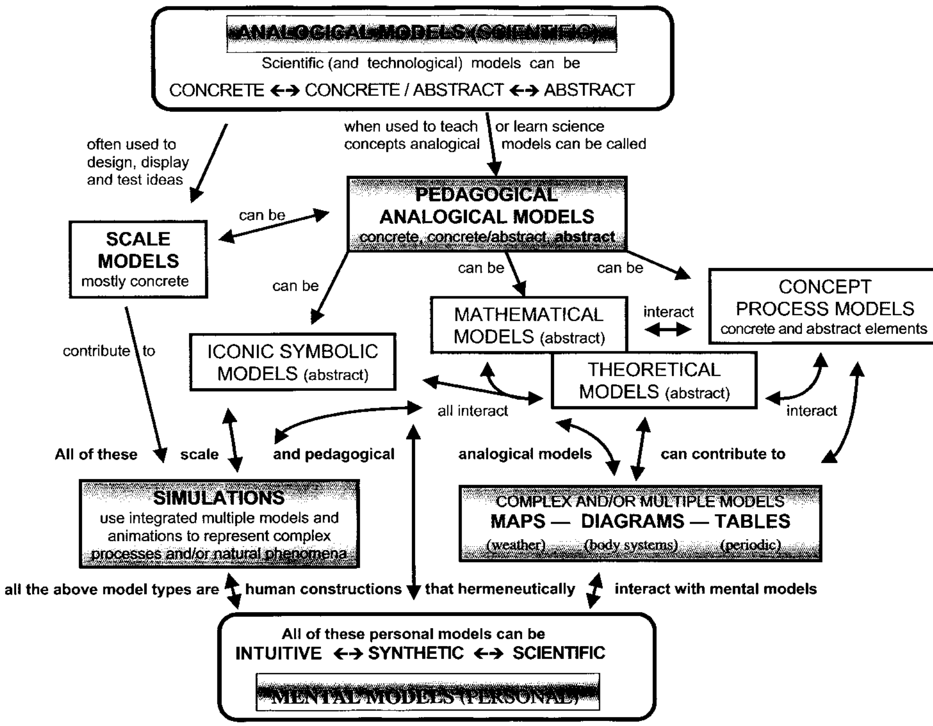

Figure 1. A concept map of the typology of concept-building analogical models.

(Keenan *et al.* 1980). Because analogical models reflect point-by-point correspondences between the analogue and the target for certain attributes, analogue attributes often are oversimplified or exaggerated (atoms are solid balls, bonds are sticks joining the balls) to highlight conceptual attributes. This category is now elaborated as:

Pedagogical analogical *models that build conceptual knowledge*

3. Iconic and symbolic models

Chemical formulas and equations are symbolic models of compound composition and chemical reactions (Pimental 1963, Feynman 1994). Formulas and equations are so embedded in chemistry's language (Sutton 1992) that school students and non-specialist teachers mistake them for reality when they are, in fact, explanatory and communicative models. Formulas and equations need to be interpreted; for instance CO_2 is thought to represent carbon dioxide but to be more accurate, it needs transforming into OCO, O═C═O and so on. And what holds for CO_2 won't work with H_2O!

4. Mathematical models

Physical properties and processes (e.g. $k = PV$, $F = ma$), can be represented as mathematical equations and graphs that elegantly depict conceptual relationships - e.g. Boyle's Law, exponential decays, etc. - (Black 1962, Hodgson 1995).

Kline's (1985) view is 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; therefore, the ideal nature of these models should be recognized. It also is important that students construct, for themselves, verbal or written qualitative explanations for mathematical models (Hewitt 1987).

5. Theoretical models

Analogical representations of electro-magnetic lines of force and photons (Gee 1978, Smit and Finegold 1995) are 'theoretical' because the models are human constructions describing well grounded theoretical entities. Models like the kinetic theory's explanation of gas volume, temperature and pressure belong to this category (Keenan *et al.* 1980, p. 222-224). Oversimplifying kinetic theory particles as perfectly elastic space-filling spheres also qualifies them scale models. Certain phenomena may share theoretical and mathematical attributes (Black 1962).

Models depicting multiple concepts and/or processes

6. Maps, diagrams and tables

These models represent patterns, pathways and relationships that are easily visualized by students. Examples are the periodic table, phylogenetic trees, weather maps, circuit diagrams, metabolic pathways, blood circulation, pedigrees, food chains and webs. It is important to realize that the simplified and exaggerated nature of all or parts of these diagrams make them two-dimensional models. Individual students interpret diagram items and colours differently; for instance, some students believe that chlorine atoms are green.

7. Concept-process models

Many science concepts are processes rather than objects (Chi *et al.* 1994) and this presents an explanatory dilemma: how do teachers explain immaterial processes to students, most of whom think in concrete terms? Teachers and textbooks use concept-process models like the multiple models of acids and bases, redox and chemical equilibrium (Carr 1984, Garnett and Treagust 1992a, 1992b). 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 characterizing oxidation as both gain and loss. Similarly, the most effective physics explanation for the refraction of light uses concept-process models like balls, wheels or marching soldiers moving from a hard-to-soft or soft-to-hard surface (Hewitt 1987, Harrison 1994).

8. Simulations

Simulation is a unique category of multiple dynamic models. Simulations model complex and sophisticated processes like aircraft flight, global warming, nuclear reactions, accidents and population fluctuations. 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 employing animations and real-life situations). The realism of many simulations masks their analogical nature and encourages students to visualize the simulation as reality.

Personal models of reality, theories and processes

9. Mental models

Mental models 'refer to a special kind of mental representation, an analogue representation, which individuals generate during cognitive functioning' (Vosniadou 1994, p. 48). They are also intrinsic descriptions of objects and ideas that are unique to the knower and arise and evolve 'through interaction with a target system' (Norman 1983, p. 7). Mental models need not be technically accurate, but they must be functional and 'people may state (and actually believe) that they believe one thing but act in quite a different manner' (p. 11). Thus, the mental models students create and use can be 'incomplete . . . unstable . . . do not have firm boundaries . . . unscientific . . . parsimonious' (p. 8). To some degree, all students interpret textbooks and teacher models; that is, *they* decide what the model is saying to them about a concept and what it is not saying. This raises the question: can people apply and communicate all their mental models? Kline (1985) suggests that people 'consciously construct and apply geometries that exist only in human brains and that were never meant to be visualised' (p. 179). Mental models provide 'the associated imagery' (Sutton 1992, p.8) that makes modelling an effective thinking and working scientifically tool but also means that mental models are highly personal, dynamic and difficult to access.

10. Synthetic models

Vosniadou (1994) used this term to describe the evolving alternative conceptions students' synthesise as they meld their intuitive models with their teachers' scientific models (also Strike and Posner 1992). For instance, many chemistry students learn about atoms through a model sequence of elastic balls, solar system atom, shells, clouds, levels and orbitals. Harrison and Treagust (1996) found that some middle school students believed that electron shells were protective structures like egg and clam shells and that an electron cloud was a matrix in which electrons were embedded. Synthetic models like these are common products of science lessons.

There is a sense then, in which mental models subsume all the above categories. For more detailed discussions of mental models see Craik (1943), Gentner and Stevens (1983) and Johnson-Laird (1983).

Learning and teaching with models

Categories 1-8 are called analogical models because each model is a simplified or exaggerated representation of an object or process. The models are analogical because evident point-by-point mappings between the analogue model and the science phenomena describe and explain structures and functions. They range from 'concrete' scale models like model cars, plants, and animals through to highly 'abstract' theoretical models like magnetic fields and concept-process models of, for example, chemical equilibrium and homeostasis.

Analogical model = 'solar system' model	Target = the atom
Shared attributes	
the sun has most of the mass	the nucleus has most of the mass
the sun is the centre	the nucleus is in the centre
planets are smaller than the sun	the electrons are smaller than the nucleus
planets orbit the sun	electrons orbit the nucleus
planets and the sun attract each other	electrons and nucleus attract each other
solar system is mostly space	atom is mostly space
...	
Unshared attributes:	
planets differ in size	electrons are all the same size
one planet per orbit	multiple electrons per level
planets in elliptical orbits	electrons don't orbit like planets
sun-planet force is gravity	electron-nucleus force is electrostatic

Figure 2. A way to map the solar system analogical model of an atom.

Analogical models, like analogies, can be simple, enriched, or extended (Curtis and Reigeluth 1984). In a simple analogical model, the relationship between the analogue and the target is obvious without explanation (e.g. an atom is like a ball). Enrichment qualifies the mapping by stating how or when the target is like the analogue (e.g. 'stick' bonds represent the forces between grossly enlarged atomic models), An analogue is 'extended' when multiple enriched analogical models illustrate one target or an enriched analogical model informs multiple targets. Examples of extended analogies include the multiple analogue-target mappings between the eye and camera, (Glynn 1991). An 'extended' analogical model could be the solar system atom (figure 2).

Analogical models can also be located along a concrete, mixed concrete-abstract, abstract continuum. While it is assumed that concrete models are suitable for introducing concepts to students and abstract models are better for explaining more sophisticated versions of the concept, concrete models are not 'foolproof.' A concrete model may raise as many questions as it answers, if the conditions under which it is valid are not understood by the student (e.g. how an atom is like a ball).

Teachers and scientists believe that analogical models help students build and manipulate mental models of abstract and non-observable phenomena. For this reason, analogical models are regularly used to describe and explain conceptually important structures and functions. Analogical models do help learners build understanding, however, the congruence of the students' understanding with the teachers' expectations is an open question if teachers do not actively negotiate the analogical model's familiarity and its shared and unshared attributes with the students. The typology of analogical models in figure 1 is structured in a way that suggests that each model's conceptual demands, its scientific appropriateness and expected benefits increase as one moves from scale models to concept process models. For instance, a scale model of a boat is less challenging than a symbolic chemical equation and a chemical equation may be less abstract than the wave-particle duality of light (a theoretical model). When teachers choose models to explain concepts it seems important to be aware of student needs and prior knowledge, the nature of the science content (White 1994) and the type of explanation being used (Treagust and Harrison 2000).

Learning with models

Of the models used to represent science concepts, analogical models are frequently used to model macroscopic, submicroscopic, and symbolic entities (Gabel *et al.* 1992). Analogical models can be concrete (e.g. atoms represented as balls - Keenan*et et al.* 1980), abstract (a simple tube for an earthworm's gut - Ogborn *et al.* 1996) or mixed (a ball-and-stick molecular model-Keenan *et al.* 1980). Analogical models are always 'simplified' and 'exaggerated' in some way to emphasize the attributes that are shared between the analogical model and the target concept. Despite careful planning to reduce the unshared attributes, analogical models always break down somewhere. Two types of analogy operate between the analogical model and the target concept: surface similarities that quickly attract students to the intended analogy and deep systematic process similarities that develop conceptual understanding. The desired concept learning almost always lies in the systematic process similarities and students usually need guidance in mapping these relationships (Gentner 1983, Zook 1991). This partly explains Glynn's (1991) claim that analogies are 'two-edged swords' - students map the obvious analogy when the teacher expected them to map the systematic or process analogy.

Models only act as aids to memory, explanatory tools and learning devices if they are easily understood and remembered by students. Analogical models need to be familiar, logical and owned by the students. Ownership, seems to be strongest when students generate their own analogies; however, reports of student-generated analogies are rare and only Cosgrove (1995) reports success at this level. Students more easily map self-generated analogies than teacher-supplied analogies because their personal analogies are more familiar and easier to apply (Zook 1991).

Here lies the problem: students find it hard to generate or select appropriate analogies for a given situation and are most likely to apply an analogy to a concept when the teacher supplies the analogue even though they find mapping it difficult. This highlights the need for teachers to systematically plan model and analogy use in their lessons and recommends the use of an approach involving the Focus, Action and Reflection (FAR) aspects of expert teaching (Treagust *et al.* 1998). *Focus* involves pre-lesson planning where the teacher focuses on the concept's difficulty, the students' prior knowledge and ability, and the analogical model's familiarity. *Action* deals with the in-lesson presentation of the familiar analogy or model and stresses the need for the teacher and students to co-operatively map the shared and unshared attributes. *Reflection* is the post-lesson evaluation of the

FOCUS		
	CONCEPT	Is it difficult, unfamiliar or abstract?
	STUDENTS	What ideas do the students already have about the concept?
	ANALOG	Is it something your students are familiar with?
ACTION		
	LIKES	Discuss the features of the analog and the science concept.
		Draw similarities between the analog and target.
	UNLIKES	Discuss where the analog is unlike the science concept.
REFLECTION		
	CONCLUSIONS	Was the analogy clear and useful, or confusing?
	IMPROVEMENTS	Refocus as above in light of outcomes.

Figure 3. The three aspects of the FAR guide for teaching and learning with analogies and models.

analogy's or model's effectiveness and identifies qualifications necessary for subsequent lessons or modifications next time the analogy or model is used. The FAR guide for systematically presenting analogies and models is summarized in figure 3.

Student modelling abilities

The analogical model map shown in figure 1 attempts to classify the conceptual demands of learning models; however, it is useful only if it encourages teachers and writers to think about the modelling experience and expertise of their audience. Teachers should not assume that just because a student apparently understands a model heart or eye s/he can interpret magnetic field models without much more experience and help. Yet many elementary and middle school science textbooks introduce and use the magnetic field metaphor and rarely explain its origin or meaning. Students cannot be expected to understand theoretical models simply because curriculum materials and teachers decide to use them in their descriptions and explanations!

It should be remembered that Grosslight *et al.* (1991) found that most students up to and including Grade-10 are level 1 or level 1/2 modellers, that is, they are concrete, or occasionally, concrete/abstract modellers. Most secondary students believe that there is a 1:1 correspondence between the models they use and the targeted reality. While students recognize the existence of these differences, they do not consistently search for reasons to explain the apparent differences. For this reason, students need epistemologically guided lessons on how to construct and interpret analogical models. Constructivist learning theories suggest that students will need extended experience in model-based thinking and learning in a consensual environment if they are to become effective relational thinkers.

There is a degree of epistemological progression in the analogical models depicted in figure 1. Many abstract and concept-process models and practically all simulations employ several scale, iconic or mathematical models. For instance, interactive multimedia programmes explaining chemical reaction rates integrate space-filling molecular models, iconic symbols, graphs and equations; circulatory system models holistically model the heart, blood vessels and cells, pressure and fluid dynamics. If complex and sophisticated models of processes and concepts depend on simple, concrete and iconic analogical models, should not students progressively gain experience with and understand these 'simpler' models before moving onto more challenging types?

Finster (1989, 1991) argued that students should be challenged at a level that is just beyond their current intellectual achievement. This means, in psychological terms, that model-based learning should be located within the students' zones of proximal development (van der Veer and Valsiner 1991, pp. 336-340). Vygotsky described this zone as the intellectual range bounded at the lower level by what a student can do on his/her own and at the upper level by what s/he can achieve with teacher cues or peer help. This is why it is so important to socially negotiate and scaffold the meaning of difficult concepts and abstract models. Vygotsky's arguement is that student intellectual growth is optimized when they are challenged to do, with help, what they cannot do on their own. Perry's (1970) model of intellectual and ethical development makes similar claims and Grosslight *et al.*'s (1991) modelling levels suggest that modelling is an intellectual skill that develops with help and experience.

These elements - progressive development of model types and social negotiation - seem lacking in school model-based learning. For instance, chemistry and biology textbooks consistently introduce disparate multiple models without explaining the models' attributes and differences (e.g. Pimental 1963, Australian Academy of Science 1990) and most textbooks introduce and employ the 'field' metaphor without prior discussion.

Concept process modelling

The most complex and abstract models in this typology are concept-process models. They are process thinking models for understanding and applying important concepts like physical and chemical equilibrium, biological classification and current flow in network circuits. Carr (1984) points out that concept-process models like the three models of acids - (1) they are sour and react with metals to produce hydrogen, (2) Arrhenius acids produce H^+ ions and (3) Brønsted-Lowrey acids are proton donors - confuse many chemistry students. And then there are the four models of oxidation-reduction. Some of the models used in different parts of the science syllabus are even contradictory; for example, the use of conventional current (a flow of positive charge) in physics clashes with the flow of negative electrons used in electrochemistry. Maybe we should be more surprised when students are not confused by this behaviour!

Research into students' understanding of chemical equilibrium and redox consistently claims that these concepts are conceptually very challenging. The abstract nature of these concepts and the apparent contradictory form of the explanatory models highlight the need for students to be competent modellers before receiving concept-process models. This makes a strong case for broadening students' experiences in thinking and working scientifically with multiple models throughout their science courses.

Multiple explanatory models

Many science concepts depend on multiple models for their description and explanation. The more abstract and non-observable a phenomenon, the more likely it will utilize multiple models (e.g. atoms and molecules, equilibrium and redox) because each model elaborates but a fraction of the target's attributes. In many cases, the sum of a concept's models is less than the whole phenomenon for two reasons: the concept itself is not fully understood, and the models tend to overlap. There are sound reasons why no single model can fully illustrate an object or process for, if it did, it would be an example not a model. Expert teachers mostly use models to stress and explore important and difficult aspects of a concept and this is best achieved by over-simplifying the model to emphasise key ideas. This is why multiple models are so useful because a series of simplified models can be used to explain, one at a time, the key ideas.

There is another good reason for using concurrent multiple models. The use of quite different simplified and/or exaggerated representations of the same concept at the same time signals to students that no model is complete or 'right'. Research by Harrison (1996) supports the claim that continual exposure to multiple models did help a significant proportion of a class of Year-11 chemistry students begin to realize that models are thinking and explanatory tools, not reality.

But nearly every textbook we have examined fails to warn its readers that models are human inventions that break down at some point. Teachers also may assume that their students understand the limits of in-class analogical models; however, Grosslight *et al.* (1991) show that this belief is mostly unfounded. This raises a major thinking and learning problem for students. Students need time and help in coming to realize that models are contrived and limited representations of reality. According to Grosslight *et al.*, the legitimacy of multiple scientific models is a function of epistemological expertise; however, middle school students are usually level 1 modellers who believe that one model is right. It is not surprising, then, that students are perplexed when teachers and textbooks at this level move from one model to another without explanation. Inexperienced students believe that the teacher knows the right model and the trick for them is to discover which model is right (Perry 1970). In contrast, modelling that is multiple, flexible, purposeful and relational is the essence of thinking and working scientifically (e.g. Mayer 1992, Gilbert 1993) but is rarely found in school students. The pressing question for school science education is: How can students with naive and realist worldviews be encouraged to progressively develop expert modelling skills?

This is where we believe the typology of school science models is useful. Figure 1 outlines the level of conceptual difficulty inherent in each model type and model types 1-8 are ordered in an attempt to reflect their conceptual demands.

Awareness of these demands should encourage teachers to match the model types they use in their lessons to their students' conceptual ability. The previously mentioned approach for teaching with analogies and models (FAR), is a framework that teachers can use to systematize their students' model-based learning. Similarly, it is recommended that teachers introduce models that are situated within the students' 'zone of proximal development.'

Where to now?

The model typology and teaching recommendations presented in this paper may have raised ideas and questions in reader's minds. We too are curious about where this research will lead us because the typology continues to evolve and we have many unanswered questions about how mental models develop during learning. From our perspective, some of the issues and questions needing further research include:

(1) What are teachers' and students' perceptions of the scope and limitations of models?
(2) How do students interpret and visualize their teacher's and textbook's models?
(3) Can the model typology be refined to better reflect the ways scientists, students and teachers use individual and multiple models?
(4) Which learning conditions encourage students to modify supplied models or build their own models?
(5) Does the FAR guide enhance the way teachers teach and students learn in science?
(6) Why are students reluctant multiple modellers and what motivates multiple model use?

Conclusion

This article has shown that a wide range of teaching models regularly feature in secondary science lessons. These models range from concrete scale models depicting no more than superficial features through to abstract concept-process models using multiple models to represent sophisticated scientific processes. The article focused on two main themes. First, the analogical models used in science can be arranged in a model typology (figure 1) that helps teachers understand the conceptual demands different model types place on students. At the same time, Grosslight *et al.*'s (1991) modelling levels highlight the need for teachers to sequence their model use in ways that develop student modelling skills by gradually challenging students to use more abstract and difficult models. Second, the article points out that no single model can ever adequately model a science concept; therefore, students should be encouraged to use multiple explanatory models wherever possible. This is best done by teachers modelling multiple modelling in their lessons. In its simplest form, this requires teachers to avoid early closure in discussions by asking the students for 'another model please.' It also asks teachers to socially negotiate model meanings with their students and to regularly remind students that all models break down somewhere and that no model is 'right'.

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