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RESEARCH REPORT

What Teachers of Science Need to Know about Models: An overview

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The purpose of this article is to provide an overview of the nature of models and their uses in the science classroom based on a theoretical review of literature. The ideas that science philosophers and science education researchers have in common about models and modelling are scrutinised according to five subtopics: *meanings of a model*, *purposes of modelling*, *multiplicity of scientific models*, *change in scientific models* and *uses of models in the science classroom*. First, a model can be defined as a representation of a target and serves as a 'bridge' connecting a theory and a phenomenon. Second, a model plays the roles of describing, explaining and predicting natural phenomena and communicating scientific ideas to others. Third, multiple models can be developed in science because scientists may have different ideas about what a target looks like and how it works and because there are a variety of semiotic resources available for constructing models. Fourth, scientific models are tested both empirically and conceptually and change along with the process of developing scientific knowledge. Fifth, in the science classroom, not only teachers but also students can take advantage of models as they are engaged in diverse modelling activities. The overview presented in this article can be used to educate science teachers and encourage them to utilise scientific models appropriately in their classrooms.

Keywords: *Model; Modelling; Scientific model; Science teachers; Science classroom*

Introduction

The school science curriculum should elucidate proper notions of science which characterise the intellectual and cultural traditions of the scientific community (National Research Council [NRC], 1996). In the 1960s, Black (1962) argued that models played distinctive and irreplaceable roles in scientific investigations and suggested a classification of models including scale models, analogue models,

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mathematical models and theoretical models. Hempel (1965) also acknowledged the importance of models in scientific explanations, saying: 'explanatory accounts offered in empirical science are sometimes formulated in terms of a "model" of the phenomena to be explained' (p. 433). Presently, far more authors consider model-based views of scientific theory and scientific enquiry valid in depicting the practice of science (Bailer-Jones, 2002; Giere, 1988, 1999a; Gilbert, 2005a; Grandy, 2003; Magnani & Nersessian, 2002; Magnani, Nersessian, & Thagard, 1999; van der Valk, van Driel, & de Vos, 2007). In short, the model-based views state that developing scientific knowledge and implementing scientific enquiry are most often accompanied with the construction and testing of models. This is different from the older view of scientific theory in which a theory is believed to be a set or system of axiomatic statements in symbolic language (Suppe, 1972). This perspective is also distinguished from the traditional psychological view of reasoning which treats reasoning as a process of employing logical algorithms to propositional representations (Nersessian, 1999). In the model-based views, models are considered subsets of scientific theories—more comprehensive systems of explanations—which are created with various semiotic resources and provide semantically rich information for scientific reasoning and problem solving (Giere, Bickle, & Mauldin, 2006; Nersessian, 1999; Windschitl & Thompson, 2006).

Given the model-based philosophical stance towards scientific theory and enquiry, science education researchers have awoken to model-based approaches to teaching and learning science in schools (e.g. Clement, 2000; Gilbert, 2005b; Gilbert & Boulter, 2000; Gilbert, Reiner, & Nakhleh, 2008). Especially in the context of earth science and chemistry education, using models is given even greater importance because the disciplinary research depends heavily on models in diverse formats (Gilbert & Ireton, 2003; Gobert, 2000; Kozma & Russell, 2005; Nakhleh & Postek, 2008; Reynolds et al., 2005; Rogers, 2008; Rowley-Jolivet, 2004). Further, quantitative and qualitative evidence has been reported for positive effects of model-based pedagogies on science learning across different subject areas and grade levels (e.g. Gobert & Clement, 1999; Gobert & Pallant, 2004; Khan, 2007; Rotbain, Marbach-Ad, & Stavy, 2006; Schwarz & Gwekwerere, 2007; Schwarz & White, 2005).

It is suggested that the application of model-based views in science classrooms requires clear understanding of the nature of models and modelling in science. Previous studies have shown, however, that teachers' perceptions of models were complex and sometimes inconsistent and that they adopted different approaches to using models in their instructions, depending on their knowledge, beliefs and experiences (Justi & Gilbert, 2003; Henze, van Driel, & Verloop, 2007; van Driel & Verloop, 2002). Therefore, it is indispensable for teachers of science to be aware of the valid notions of models in order that they can use models effectively in their science classrooms. It is also important that science teacher educators be informed and have a strong literature foundation upon which this understanding of models rests so that they can educate science teachers and investigate the effective practices with modelling in science classrooms.

In consideration of the need of teachers' understanding of scientific models and the envisioned mechanism through which they can be informed about models (e.g. working closely with university science educators to plan, implement and research effective modelling strategies), this article aimed to present an overview of the nature of models and their uses in the science classroom for science teacher educators and subsequently for science teachers. In fulfilling this goal, the article identified five subtopics concerning the nature of models and modelling and found the views that science philosophers and science education researchers have in common about the topics. The subtopics were elicited from previous studies which dealt with the perceptions of diverse groups of participants, including science teachers, on models and modelling (Grosslight, Unger, Jay, & Smith, 1991; Justi & Gilbert, 2002a, b, 2003; Smit & Finegold, 1995; van der Valk et al., 2007; van Driel & Verloop, 1999, 2002; Windschitl & Thompson, 2006). For example, researchers have indicated that their participants at times thought of models as mere copies or replicas of physical realities. Accordingly, the theme 'meanings of a model' was selected as one of the subtopics to be discussed to inform science teachers as well as science teacher educators. Likewise, the other four subtopics about models and modelling in science and science education were developed: *purposes of modelling*, *multiplicity of scientific models*, *change in scientific models* and *uses of models in the science classroom*.

In an attempt to provide an overview of models and modelling, a wide range of literature in the field of philosophy of science and science education research were examined. While it was not a possible option to locate all the articles on models, those which offered useful ideas for the five subtopics selected were read more thoroughly in the review process. In order to find literature to review, the Education Resources Information Center (ERIC) was consulted first by using 'model', 'modelling', 'science', 'scientific model' and 'scientific modelling' as keywords to appear in titles. Reading the matched articles helped identify authors who published a series of research papers on models and whose publications were cited several times by a number of other researchers. The articles of these authors were then retrieved from academic journals and books for further reading. In addition, highly recognised journals in the field of science education, e.g. those indexed in the Social Sciences Citation Index (SSCI) and Scopus, were perused periodically to find the latest literature addressing relevant topics. The literature found in the journals was read carefully to identify new issues and information concerning the five selected subtopics about models and modelling. Consequently, more thorough review was done to three groups of published literature. First, articles and books written by several active researchers on models and modelling were explored. Examples of such literature included Clement (1989, 2000, 2008; Clement, Zietsman, & Monaghan, 2005), Giere (1988, 1999a, b; Giere et al., 2006), Gobert (2000; Gobert & Clement, 1999; Gobert & Pallant, 2004; Gobert, Snyder, & Houghton, 2002), Halloun (2004, 2007), Gilbert (2005a, 2008; Gilbert, Boulter, & Elmer, 2000; Gilbert, Boulter, & Rutherford, 1998), Nersessian (1992, 1999, 2002), Schwarz (Schwarz & Gwekwerere, 2007; Schwarz & White, 2005; Schwarz et al., 2009), and Windschitl (Windschitl & Thompson, 2006; Windschitl, Thompson, &

Braaten, 2008). Second, much attention was paid to special issues of professional journals, which included the *International Journal of Science Education*, 22(9), 2000, Model-Based Teaching and Learning in Science Education and *Science & Education*, 16(7–8), 2007, Models in Science and in Science Education. Third, edited volumes dealing with the model-based views of scientific practice, and science teaching and learning were included in the review. These were *Model-Based Reasoning in Scientific Discovery* edited by Magnani et al. (1999); *Model-Based Reasoning: Science, Technology, Values* by Magnani and Nersessian (2002); *Developing Models in Science Education* by Gilbert and Boulter (2000); *Visualization in Science Education* by Gilbert (2005b); *Model-Based Learning and Instruction in Science* by Clement and Rea-Ramirez (2008); and *Visualization: Theory and Practice in Science Education* by Gilbert, Reiner, and Nakhleh (2008).

In the following sections, an overview of the nature of models and their uses in the science classroom are presented and discussed according to five subtopics, each of which represents an important issue related to models and modelling in science and science education. Implications for science teaching and learning in schools are also suggested in the 'Summary and Conclusion' section.

An Overview on Models in Science and Science Education

Meanings of a Model

Although there is wide agreement that models are important elements in scientific practice, no unique definition of a model is established. Even scientists who believe that models are central to their research conceive the meaning of a model differently from one another (cf. Bailer-Jones, 2002; van der Valk et al., 2007). However, the term 'representation' is commonly used to explain what a model is. Gilbert and Ireton (2003) suggested, for example, 'a model is a system of objects or symbols that represents some aspect of another system' (p. 1). Also, Windschitl and Thompson (2006, p. 784) viewed models as representations of how some aspect of the world works, and Schwarz and Gwekwerere (2007, p. 160) defined scientific models as representations that embody portions of scientific theories. Simply speaking, a model is something that represents something else. A miniature volcano represents a real volcanic mountain, and the Big Bang model in astronomy represents an idea about the birth of the universe. In the context of science education, the term 'mental model' is frequently used, denoting a form of mental representation that may preserve the structure of the thing it represents (Vosniadou, 2002).

There is great variance in what can be represented by a model, including observable or unobservable objects and phenomena, their properties and states, cognitive or natural processes, sequences of events and ideas of how the world works. At first glance, models are simplified or exaggerated versions of some objects. Scale models, such as a toy-size model of the space shuttle and plaster model of a volcanic mountain, are built as perceptually similar to their targets by enlarging or reducing the external shapes and structures of the targets at different rates (Gilbert

& Ireton, 2003; Harrison & Treagust, 2000). But models do not only represent real-world systems by the process of mirroring or mimicking nature (Koponen, 2007). Rather, scientific models can be created in novel ways to express abstract ideas and include theoretical entities. For example, Giere (1999b) argues that Newton's gravitational law should be understood as a theoretical model since it defines idealised objects, for example, mass point and centre of mass, and is not perfectly similar to a real-world system.

The thing represented through a model is often called a 'target' or 'referent'. A model, however, need not represent everything of a target because representation does not merely mean resemblance. Suarez (1999) asserts that 'resemblance is neither sufficient nor necessary for representation' (p. 77) and that 'a model is typically representational because it is intended for a particular phenomenon or type of system' (p. 81). Giere (1999a; Giere et al., 2006) contends as well that a model is similar to the world only in the intended respect and to the intended degree of accuracy. In other words: 'if a model were exactly like its target, it would not be a model but a copy' (van der Valk et al., 2007, p. 471). A model represents specific aspects of a target which are selected by a modeller with a certain purpose. In this regard, Halloun (2004) viewed a model as a partial representation of a specific *pattern* in the real world. Based on interviews with professional scientists in various subjects, Bailer-Jones (2002) also concluded that models can be characterised by simplification and omissions with the aim of capturing the *essence* of what is represented. More specifically, Marquez, Izquierdo, and Espinet (2006) suggested that a model is understood via its three major components: *material components*, which are parts of entities of a target, *dynamic components*, which refer to relationships among its parts or entities and *causal components*, which mean causes and functioning of a target. Thus, authors commonly indicate that a model represents only partial, selected features of its target.

Based on the discussion thus far, a model can be defined as a representation of objects, phenomena, processes, ideas and/or their systems (Gilbert & Boulter, 2000, p. vii). This definition is exclusive enough to prevent what indicates something directly or describes it literally from being treated as a model. The definition also implies that a model does not interact directly with its target but exists only via the modeller's interpretation of the target and his/her purpose of model making (van der Valk et al., 2007). For instance, a growth curve of organic population is a mathematical model because a population comprises distinct individuals and its growth cannot literally be continuous (Giere, 1999b). Contrarily, a photo of a tornado can hardly be a model unless it is intended to represent a particular aspect of a real tornado.

In a pragmatic sense, a model is often compared to a 'bridge' or regarded as a 'mediator' since a model plays a role of making a connection or transition between theory and phenomenon (Koponen, 2007; Morrison & Morgan, 1999; Rotbain et al., 2006). The bridging or mediating role of a model comes from the facts that a scientific theory has no direct correspondence to real-world entities and that the natural phenomena are often too complex to fit readily to any theoretical pattern as such (Koponen, 2007). It is through a scientific model that a theory is connected to a phenomenon. For example Koponen (2007) explained how a model mediates a physics theory and experiment as follows:

> The measurable properties of phenomena and entities thus provide us with the necessary core of any physical theory. The abstracted and idealised descriptions of these experimental results were once referred to … as *experimental laws*. It is this kind of experimental law—a kind of 'model of data'—that the theoretical models constructed in physics are meant to be matched with. The form of models … mediates between high-level theory and experimental laws, in the above sense. (p. 762, emphasis in original)

Similarly, Giere (1988, 1999a) and Halloun (2004) contend that a model exists in the middle of theoretical statements and real-world objects, connecting the two entities like when the pendulum theory applies to actual pendulums through a family of idealised models (cf. Giere, 1999a). Halloun (2004) further argues that the transition between theories and phenomena is bi-directional:

> [Models] may or may not be conceived by *re*construction of a set of physical realities. In the former event, the conceptual reconstruction is partial. It is done within the framework of an appropriate paradigm in order to display the best specific primary details in the corresponding physical realities and optimize their exploitation. In the latter event, i.e., when our idealized conceptual realities do not consist of conceptually *re*constructed physical realities that are known to us and are exposed to our senses in one form or another, these conceptual realities may be constructed following conjectures about the existence of some physical realities that are as yet unknown. (p. 27, italics in original)

In other words, phenomena can be organised, through the processes of idealisation and abstraction, into a model, which in turn provides useful insight for the development of a new theory. In reverse, a scientific theory may be reified into a model which is mapped onto and explains some patterns in the natural world. For example, it is a well-known historical fact that Galileo's postulation of the idea of inertia started from his observation of the pendulum motion and proceeded in constructing idealised models and developing a more comprehensive scientific principle (Losee, 2001). In contrast, scientists can create models through pure rational inference which contain objects thought not to exist in the real world, such as the shapeless and dimensionless particle model in mechanics, Gell–Mann's model which first predicted the existence of quarks and Bohr's atomic model (Halloun, 2004). These models serve to obtain new information about phenomena whose underlying theoretical processes are not accessible to direct or indirect observation.

To sum up, although definitions of a model may be diverse, a model is understood as a representation of a target. The targets represented by models can be various entities, including objects, phenomena, processes, ideas and their systems. A model is also considered a bridge or mediator connecting a theory and a phenomenon, for it helps in developing a theory from data and mapping a theory onto the natural world.

Purposes of Modelling

An essential characteristic of scientific models can be understood through the analysis of the purposes for which scientists use models. Many authors are in agreement that as description, explanation and prediction are primary goals of science, the purposes of modelling in science are to describe, explain and predict particular aspects of the natural world (Buckley & Boulter, 2000; Gilbert et al., 1998; Halloun, 2004; Shen & Confrey, 2007). Here, a description refers to a statement of how things exist or behave, while an explanation means an account of why things exist or behave in one way or another (Halloun, 2007). In other words, descriptions are answers to the ontological question of what exists, whereas explanations are answers to the causal question of why things happen. Besides the roles of describing, explaining and predicting, a model serves as a communicative aid in social contexts where scientists share their knowledge and understanding with their peers or the public.

Then how does a model fulfil the roles of describing, explaining, predicting and communicating, and how are these functional roles of a model different from those of other scientific elements such as a propositional theory?

First of all, a model provides non-linguistic representations of its target (Giere, 1988, 1999a, b; Nersessian, 1992, 1999). Models are often characterised as the use of visual resources, such as pictures, diagrams, animations or material objects, which simplify and highlight certain aspects of the targeted systems. By virtue of the simplification and visualisation processes, some models can illustrate phenomena that are complex and not easily accessible to direct observation. Especially, visual representations organise lots of information together and make complicated reasoning processes tangible so that they can guide and support perceptual inferences. For example, Maxwell grasped specific structures inherent in Faraday's imagistic representation of magnetic force and used them to construct a mathematical field representation (cf. Nersessian, 1992). Also, visual models such as Wegener's representation of the break up of the super-continent, Holme's diagrams of convection currents, and Hess's model of sea floor spreading and magnetic profiles near oceanic ridges played a central role in developing the plate tectonics theory by providing persuasive accounts of the revolutionary idea in the twentieth-century geology (cf. Giere, 1988, 1999a).

Many authors agree that the explicative capability of a model comes from the use of analogy (Dunbar, 1999; Giere, 1999b; Nersessian, 1992). Analogy is used in 'a modeling process in which relational structures from existing modes of representation and problem solutions are abstracted from a source domain and are fitted to the constraints of the new problem domain' (Nersessian, 1992, p. 20). The history of science provides rich evidence that scientists have employed analogical reasoning so often in their work. For example, Kepler made use of analogy deliberately when developing his own causal model of planetary motion. According to Gentner (2002), Kepler's analogical reasoning consists of four subprocesses—highlighting common structure, projecting inferences, re-representing relations and noticing alignable differences—by which analogy produces new ideas. Giere (1999b) explains how scientists use analogy when they confront a new problem:

> Scientists have at their disposal an inventory of various known phenomena and the sorts of models that fit these phenomena. When faced with a new phenomenon, scientists may look for known phenomena that are in various ways similar to, which is to say,

> analogous with, the new phenomenon. Once found, the sorts of models that successfully accounted for the known phenomena can be adapted to the new phenomenon. In the process, features of the old models may suggest unknown features of the new phenomenon. (p. 56)

Further, Dunbar (1999) distinguishes *local* and *distant analogies* that scientists utilise to build models. The local analogies are made by using knowledge from similar contexts as analogical sources of models, while the distant analogies are based on knowledge from very different domains. According to Dunbar (1999), scientists usually take advantage of local analogies when they are to construct a new model, and, in contrast, distant analogies are used primarily to explain difficult concepts to others.

The purposes of modelling are facilitated as the model makes it possible to simulate the phenomenon of interest mentally and externally. According to Johnson-Laird (1983), a scientific theory can exist in at least three forms of representation: propositions, mental models and images. Out of these, mental models are considered structural analogues of real-world or imagined situations. Mental simulations take place with these mental models when situations are visualised as envisioned by the mental models, a scenario of the situations runs in the mind and the results are observed with the mind's eye (Nersessian, 1999; Reiner & Gilbert, 2008). Simulations with models also occur externally with physical representations of natural phenomena (Morgan, 2002). Especially, current computer models provide effective ways of experimenting virtually in complex environments or idealised situations (Carmichael, 2000). These internal and external simulations with models enhance our reasoning and communication by providing information about the targets that are inaccessible first hand or which otherwise would require very complicated manipulations with real-world objects. For example, Nersessian (1992) remarks about the benefits of model simulations when saying: 'certain features of objects that would be present in a real experiment are eliminated, such as the color of the rocks and the physical characteristics of the observers. That is, there has been a prior selection of the pertinent dimensions on which to focus' (p. 33).

In summary, a scientific model as a thinking and communicative device serves the purposes of describing, explaining and predicting natural phenomena and communicating scientific ideas to others. These functional roles of models are leveraged by expressing models with non-linguistic semiotic resources, using analogy and allowing mental and external simulations.

Multiplicity of Scientific Models

The multiplicity as a characteristic of scientific models means that different models can be constructed for the same target. Based on the claim from cognitive research that the variability may provide cognitive flexibility for one to employ different tools for different tasks, Miller (2001) hypothesised that scientists using a variety of models might be more creative scientifically. As he expected, scientists use diverse models when they are engaged in solving scientific problems and in explaining complex concepts of science (Giere, 1988, 1999a; Snyder, 2000). Of course, as van der Valk et al.'s (2007) study revealed, there may be a situation in which scientists decide to do research with only one model. But their decision is probably related to the research question and its specific context, and in principle, different models can represent the same target (cf. van der Valk et al., 2007). Then why does there exist multiple models in science? Researchers have provided some reasons for this.

First, since a model represents a target in a special way depending on the kind of problem or the intention of the modeller, different models can be constituted to represent different aspects of the same system. For example the Earth's motion can be considered a target for four different models: a particle model for Newtonian mechanics, a rigid body model for Euler theory and two sidereal cycle models, that is, seasonal cycles and day and night cycles, for earth and biological sciences (Halloun, 2004). Furthermore, the same physical object may be used to construct different models. Suarez (1999) takes a spiral staircase as an example: 'a spiral staircase … could be used to represent DNA. The very same staircase could also be taken, for instance, to represent a spring' (p. 82). In this case, it can be easily recognised that what makes a spiral staircase a model of DNA or spring is not the physical properties of the staircase but rather the modeller's interpretation of the target system.

Second, the fact that a model only represents selected features of a target entails that a model always has limitations and so various models are needed to provide a full-fledged explanation of a real-world system. 'When we need to represent the same pattern with different levels of precision', Halloun (2004, p. 44) states, 'we have to resort to different models belonging to different scientific theories within or without the same paradigm'. For instance, to understand the structure of the universe, we rely on many different models produced from different sorts of instruments such as optical telescopes, radio telescopes and infra-red detectors (Giere, 1999a). In this case, it does not matter whether or not each instrument provides the full perspective of the universe, because all the instruments generate models of the reality even though the models are always partial and each model is valid only for a particular objective.

Third, two or more rival models may coexist because there are multiple ways of explaining or conceptualising the same thing in science (Grosslight et al., 1991). Roughly speaking, the history of science is that of constructing explanatory models, testing them and selecting better ones among many alternatives. It is well known that by Wegener's time, several different models, including contractionist and lateral stabilist models, had been suggested to explain the puzzle fit of the coastal lines of African and South American continents (Giere, 1988, 1999a). Also, two distinguished models are competing and providing complementary explanations for the late Pleistocene megafaunal extinction (Guthrie, 1984; Martin, 1984). Positively, such multiple rival models in science can promote more active enquiry and contribute to the progress of scientific understanding of the phenomenon in question.

Another reason for the multiplicity of scientific models is that models may be created in multiple forms of representation. The model-based views do not support the belief that scientific knowledge is provided by only a particular formation of a theory, such as linguistic and mathematical entities (Izquierdo-Aymerich & Aduriz-Bravo, 2003). Rather, as many authors pointed out (Boulter & Buckley, 2000; Gilbert, 2008; Gilbert & Ireton, 2003), any semiotic resources, including linguistic entities, pictures, diagrams, graphs, concrete materials, animations, actions, gestures and their combinations, can be used for building scientific models. The US National Science Education Standards (NRC, 1996) specifies this notion by stating:

> Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power. … Models take many forms, including physical objects, plans, mental constructs, mathematical equations, and computer simulations. (p. 117)

Thus, the scope of models goes beyond that of verbal expressions or simple images in the sense that a model can integrate visual–spatial representations with verbal and other semiotic modes (Ramadas, 2009). Especially in the domain of earth science, figurative and graphical representations are used more frequently and extensively than other subject areas (Rowley-Jolivet, 2004). This implies that the multimodality of scientific models is deeply ingrained in the disciplinary practice, reflecting the nature of phenomena investigated in earth science and the characteristics of the methods used in earth scientific enquiry. Chemistry is another academic domain in which various types of models are utilised at different levels, such as observational/macroscopic, molecular/microscopic and symbolic levels, for the purposes of research and education (Nakhleh & Postek, 2008; Rogers, 2008).

In sum, multiple models can be developed to study the same system because scientists may have different ideas about what the target looks like and how it works. Additionally, there are a variety of semiotic resources available for constructing models which also contribute to the multiplicity of scientific models.

Change in Scientific Models

One of the epistemic features of scientific knowledge is that it is revisable, which means that 'scientific ideas can change in response to new evidence or because a phenomenon is conceptualised in an entirely different way' (Windschitl et al., 2008, p. 944). Indeed, scientific knowledge has developed through ongoing inter-complementary relations between theoretical and empirical worlds. Halloun (2004) explains these 'empirical–rational dialectics' as follows:

> Such dialectics always start with the construction of a tentative model followed by the collection of appropriate empirical data that will be analyzed to test the validity of the model and subsequently make the appropriate judgment as to the acceptance, refinement or rejection of the model. In short, scientific methodology is primarily about making, testing and using conceptual models of patterns in physical realities, with the use of various conceptual tools, and following well-defined principles and rules of engagement. (p. 29)

Historically, scientists have come up with different models to explain natural phenomena, and the models have been tested and changed along with the process of developing scientific knowledge. Gilbert et al. (2000) define *consensus models* as those which are acknowledged as valid by different social groups after discussion and experimentation. Among many consensus models, *scientific models* indicate particularly those which have 'gained acceptance by a community of scientists following formal experimental testing' (Gilbert et al., 2000, p. 12). These models play central roles at the frontiers of scientific research, but later they are superseded by more developed scientific models and become *historical models*. In truth, there are a lot of examples of models in science which developed through the continuous model construction and evaluation processes, including Watson and Crick's DNA model in biology, plate tectonics model in earth science, helo- and geocentric models of the solar system in astronomy (Giere et al., 2006), models of light in physics (Rutherford, 2000) and models of acidity in chemistry (Oversby, 2000). Such scientific or historical models are simplified into *curricular models* to be included in a formal school curriculum, which are further developed by teachers or students as *teaching models* to understand scientific, historical and consensus models and their referents (Gilbert et al., 2000).

Broadly, there are two ways to test a model in science: *empirical* and *conceptual assessments* (Passmore & Stewart, 2002). Empirical assessment is a way of evaluating a model in terms of the fit between the model and the actual phenomenon. In the case of a dynamic model, simulations allow mapping the model predictions onto empirical-level facts (Morrison & Morgan, 1999). If what a model depicts or predicts is consistent with the data collected through interaction with the natural world, it becomes good evidence that the model is valid among alternatives. If there is no correspondence between what is described by a model and the real world objects, or if a conflict is found between the simulated result and the empirically obtained data, it is likely to be believed that the model needs change. In such situations, scientists may revise the existing model to fit well with the real world or invent a brand new model to explain the anomaly. The revised or newly constructed model in turn generates new hypotheses which suggest new observations and experiments about the target (Giere et al., 2006; Passmore & Stewart, 2002).

In conceptual assessment, a model is evaluated according to how well it fits with other accepted models as well as with other types of knowledge (Passmore & Stewart, 2002). For example, despite several falsifying observations, geocentric models of the movement of celestial bodies retained their prestigious status for a long time in the history of science. One of the reasons for this was that the models were congruent with the contemporary philosophy that put the Earth as the human inhabitant at the centre of the universe (Halloun, 2004). Also, it was not until a number of earth dynamics models, such as mantle convection and sea floor spreading models, matched up together to support each other that Wegener's continental drift model was considered for genuine scientific enquiry (Giere, 1988, 1999a). Such historical facts corroborate that scientific models are subject to not only empirical test but also theoretical and conceptual evaluation. If a model fails to meet such evaluative scrutiny, it may be discarded or revised continuously as it is used for probing new phenomena and collecting further data (Passmore & Stewart, 2002).

It should be emphasised that although a scientific model may be changed based on new knowledge or new perspectives from empirical or conceptual tests, it is not presented as literal truth or fault. This is because a model need only reflect a specific facet of a real-world system with a limited degree of accuracy (Giere, 1999a; Giere et al., 2006). For example: ‘a model may give the bonds in a molecule correctly, but perhaps not the spatial configuration of the atoms. So one might say that a model “conforms to reality” for certain purposes’ (Bailer-Jones, 2002, p. 294).

It should also be noted that the assessment of a model is conducted differently in experimental sciences, such as physics and chemistry, and historical sciences, such as earth science. In Bailer-Jones’ (2002) interview study, a paleontologist indicated properly that testing of historical models is based on evidence from the observation of historical traces, not from experiments. Moreover, Oreskes (2002) asserts that the predictive function of a model in earth science is quite different from that in physical sciences. In physical sciences, a model is evaluated by the degree of agreement between prediction—what Oreskes (2002) calls ‘short-term prediction’—and data obtained by experimenting with the model. In contrast, models in earth science, such as global climate change models, represent very complex natural systems and are always accompanied with the problem of uncertainties which cannot be fully specified. Hence, the prediction of such models—what is called ‘long-term prediction’—should not be evaluated by the degree of accuracy. But rather, it should be appraised in terms of ‘what if’ scenarios which are generated by the model outputs and help us to evaluate alternative courses of future actions. According to Oreskes (2002), recognising such characteristics of long-range model predictions is very important to understand the nature of scientific modelling as well as to make relevant public policies.

Uses of Models in the Science Classroom

In the science classroom, the teacher can take advantage from using models to demonstrate how things work and explain sophisticated knowledge of science. The teacher’s use of models is justified by the idea that external presentations of visual representations provide support for constructing and reasoning with internal representations—mental models (Buckley & Boulter, 2000; Gilbert & Ireton, 2003; Nersessian, 1999). Nersessian (1999) explains how external models help the mental processes:

> They [externally presented models] aid significantly in organizing cognitive activity during reasoning, such as fixing the attention of the salient aspects of a model during reasoning, enabling retrieval and storage of salient information and exhibiting salient interconnections, such as structural and causal, in appropriate co-location. Further external visual representations … facilitate the construction of shared mental models in a community. (p. 17)

There are also research findings from different subject domains, such as physics, chemistry, earth science and biology, that external simulations with models enhance students’ mental simulations in related topics (Buckley, 2000; Clement et al., 2005;

Reynolds et al., 2005; Russell & Kozma, 2005). Furthermore, evidence shows that when models in multiple forms of representation are presented in an appropriate manner, it fosters effective learning (Adadan, Irving, & Trundle, 2009; Ainsworth, 2008; Tsui & Treagust, 2003). This positive result is explained as in the case when information coded in different modes utilises different subsystems in a learner's working memory, reducing the load of a single subsystem (Rapp & Kurby, 2008). Alternatively, Ainsworth (2008) suggests that multiple representations serve three distinct functions for learning and communication: *complementary roles* which allow different aspects of phenomena to be represented in ways that are appropriate to different needs, *constraining learners' interpretations* by familiarity and inherent properties and *constructing deeper understanding* through the processes of abstraction, extension and relation.

It can thus be concluded that the external presentation of models plays important roles in guiding students to interpret and understand the targeted systems and build their own mental models. In fact, science lessons include a number of models created through diverse media and representation methods (Boulter & Buckley, 2000; Lemke, 1998). We can consider, for example, a case of Kepler's laws of planetary motion. The classroom representation of these laws typically includes pictures of the planetary system, several equations and tables and graphs for physical properties of the planets. Although these multiple models can all contribute to our understanding of the subject and problem solving in relevant domains, it should be noted that the effectiveness of such multimodal representations often depends on learners' knowledge and their meta-visual capabilities (Ainsworth, 2008; Gilbert, 2005a). Therefore, teachers of science as well as students should develop their 'visual literacy' or 'meta-visual capability' (Gilbert, 2005a, 2008) in order to interpret diverse models properly and construct more advanced ones in their instructions.

In spite of the fact that the teacher's presentation of models is beneficial to students' learning, because it helps the teacher reformulate scientific ideas in the form more readily accessible to students, such teacher-initiated ways of using models are limited in consideration of the dynamic nature of scientific models and modelling. Uses of models in the science classroom should go beyond the conventional way, which often focuses on the transmission of the knowledge content of scientifically accepted models. Concerning the manners in which teachers use models in their science classrooms, researchers have suggested a possible relationship between teachers' perceptions and their teaching practices. For example, Windschitl and Thompson (2006) argued: 'if teachers believe a model is an unproblematic representation of a real-world structure or process, they are less likely to value its development by students or value helping students understand the nature and function of models' (pp. 818–819). In addition, it is hardly expected that teachers use models in enquiry learning activities for students if they focus only on the communicative role of models, rarely recognising that models can be used to derive hypotheses or predictions, provide informative feedback to improve theories and generate new research questions (Smit & Finegold, 1995; van Driel & Verloop, 1999). Therefore, teachers of science need to understand the nature of models and modelling in science more clearly and reflect this understanding in their science instructions.

One of the tenets of using models in science education is students' active participation in diverse modelling activities. Hence, researchers have identified the ways in which scientists use models in their professional work and adapt them in student-centred methods of using models to learn science. For instance, from the cognitive-historical perspective of scientific practice, Nersessian (2002) suggests that model-based reasoning involves construction and modification of models. Similarly, Clement (Clement, 1989, 2008; Clement & Rea-Ramirez, 2008) portrays scientific enquiry as progressive model construction and revision, and proposes a similar recurring cycle for student learning with models and modelling. Inspired by Karplus' learning cycle, Halloun (2004) also conceptualises a modelling learning cycle consisting of five consecutive phases: exploration, model adduction, model formulation, model deployment and paradigmatic synthesis. This modelling learning cycle allows students to reflect on and improve their own models in the process of paradigmatic evolution towards scientific models. In addition, van Joolingen (2004) distinguishes three modelling activities which can be incorporated with student learning in the science classroom: *exploratory modelling*, in which students investigate the properties of models by changing parameters and observing the effects of these changes; *expressive modelling*, in which students create models to express their ideas about particular subjects; and *enquiry modelling*, in which students construct models that can explain the outcomes from experimenting with phenomena and predict new ones.

As a variety of student-centred modelling activities exist, there is also evidence that learners' engagement with modelling processes makes their learning more meaningful. Schwarz and colleagues (Schwarz & Gwekwerere, 2007; Schwarz & White, 2005) argued that the modelling process in modern science involved embodying key aspects of theory and data into a model, evaluating the model using several criteria and revising the model to accommodate new theoretical ideas or empirical findings. Based on this notion, the researchers suggested that model-centred student enquiry should also focus on creation, testing and revision of models. Their instructional framework for student modelling activities is called EIMA, standing for Engage-Investigate-Model-Apply, and it proved to be effective for supporting preservice science teachers implementing reform-based enquiry teaching. In addition, Khan (2007) showed that undergraduates' sustained involvement in generation, evaluation and modification (GEM) of hypotheses resulted in their meaningful engagement with scientific enquiry and modelling process.

Student involvement in modelling activities can enhance science learning in secondary and elementary schools as well. For example Stewart and colleagues (Johnson & Stewart, 2002; Stewart, Hafner, Johnson, & Finkel, 1992; Wynne, Stewart, & Passmore, 2001) indicated that high school students used model revision strategies, such as detecting anomalies, generating hypotheses and assessing the revisions, to solve biological problems. Similarly, Maia and Justi (2009) suggested that opportunities for students to discuss and change their models were contributors to the learning process in model-based science instruction. Further, Acher, Arca, and Sanmarti (2007) and Gobert and Clement (1999) showed that even low graders could gain benefits from model construction activities to understand complex natural phenomena.

To sum up, student-centred approaches to modelling share common phases which mediate student learning in some successive cycles including exploration, expression, construction, application and revision of models. Especially, researchers emphasise that if students are allowed to build their own mental representations and present them publicly, it can result in better understanding of the targeted phenomena and processes (Ainsworth, 2008; Gobert, 2000; Michalchik, Rosenquist, Kozma, Kreikemeier, & Schank, 2008). This is because when students' mental models are expressed using external representations, they are shared, criticised and improved through interactions with classroom participants. In addition, many authors argue for incorporating modelling into scientific enquiry of students (Khan, 2007; Windschitl & Thompson, 2006). They believe that one of the major tasks of enquiry learning is to explore phenomena and construct and reconstruct models in the light of the results of scientific investigations. Thus, the student-centred modelling approach is a progressive learning process which is analogous to scientists' work of developing and testing explanatory hypotheses with the aim of achieving more sophisticated understanding of the natural world (Clement, 1989).

Summary and Conclusion

The current philosophical views on science acknowledge that models play key roles in developing scientific understanding of the natural world. Models are also believed to support science instructions in various ways. It is therefore necessary for science teachers to understand the features of models used in science and science education. It is recognised as well that science teacher educators will be important in introducing models to science teachers and a clear framework of models and modelling will be crucial to this end. On the basis of these notions, the present article has provided an overview of the nature of models and their uses in the science classroom through a theoretical review of literature. The model-based views discussed in this article are summarised in Table 1.

Quoting Schwab's claim that teaching expertise requires not only content knowledge of a domain but also epistemological knowledge of that domain, Erduran and Duschl (2004) assert that teachers can develop the capability of transforming scientific knowledge into teachable content only when they appreciate how the disciplinary knowledge is structured. Also, there is evidence that students' understanding of the nature of models and their involvements with modelling processes are correlated positively with their achievement in science learning (Gobert & Clement, 1999; Gobert & Pallant, 2004; Rotbain et al., 2006). It is therefore recommended to use the overview presented in this article to educate science teachers and encourage them to utilise models appropriately to foster effective learning of students. Further, it is hoped that the overview will better enable science teacher

Table 1. A summary of the nature of models and their uses in the science classroom

Topic	Summary
Meanings of a model	• A model is a representation of a target. • A model serves as a 'bridge' or mediator connecting a theory and a phenomenon.
Purposes of modelling	• A model plays the roles of describing, explaining and predicting natural phenomena and communicating scientific ideas to others. • The functional roles of models are facilitated by expressing models with non-linguistic semiotic resources, using analogy and allowing mental and external simulations.
Multiplicity of scientific models	• Multiple models can be developed to study the same target because scientists may have different ideas about what the target looks like and how it works and because there are a variety of semiotic resources available for constructing models. • Each model has limitations because it represents only a specific aspect of a target, and diverse models may be needed to provide a full-fledged explanation of the target.
Change in scientific models	• Models are tested empirically and conceptually, and they can change along with the process of developing scientific knowledge.
Uses of models in the science classroom	• In the science classroom, the teacher can take advantage of models to demonstrate how things work and explain sophisticated knowledge of science. • Students should have opportunities to participate in such diverse modelling activities as exploration, expression, construction, application and revision of models.

educators to follow these effective interventions and document the future impacts on science learning.

In fact, science teachers employ a number of models to teach students science, even though they do not always realise the value of using models in the science classroom (Justi & Gilbert, 2002a, b; van Driel & Verloop, 1999, 2002). In order to help the teachers appreciate their teaching practices and improve them for better student learning, this article suggests the concept of *pedagogical transformation* or what Chevallard (1988) called *didactic transposition*. The pedagogical transformation or didactic transposition refers to the instructional principle in which scientific ideas are simplified and reconstructed into what can be readily accessible to and understood by students without distorting the essential features of the ideas. This principle can be realised at the levels of both course content and learning style (Halloun, 2004). That is, the pedagogical transformation of scientific models and modelling involves not only the *model-content-oriented* approach, which emphasises the transmission of the knowledge content of models, but also the *model-thinking-* and *model-production-oriented* approaches, which encourage students to think up models to explain phenomena and create their own models (cf. Henze et al., 2007). Especially, when employing the model-production-oriented pedagogies, teachers may take advantage of the three modelling activities that van Joolingen (2004) has proposed: *exploratory*, *expressive* and *enquiry* modelling. In addition to these, the authors of this article suggest two more student-centred approaches to using models: *evaluative modelling*, in which students compare alternative models addressing the same phenomenon or problem, assess their merits and limitations and select the most appropriate ones to explain the phenomenon or solve the problem; and *cyclic modelling*, in which students are engaged in ongoing processes of developing, evaluating and improving models to complete rather long science projects. These five modelling activities reflect how scientists use models in their work to study the natural world and should therefore be considered equally important when teaching and learning science by applying the principle of pedagogical transformation.

In conclusion, the pedagogical transformation is a general idea of instruction which encompasses both teacher-led and student-centred approaches of using models, and teachers of science should be informed of this principle to make a balanced use of models in their classrooms. Collaborative action research can be considered a useful way to help teachers understand and implement the idea of pedagogical transformation. In an action research context, science teachers have opportunities to work closely with science education researchers to plan a variety of modelling activities, act on the plans and reflect on their own practices for improved plans (cf. Kemmis & McTaggart, 1988). Such collaborative efforts can also provide chances to explore how teachers accomplish the pedagogical transformation of scientific models and modelling in their classrooms and what the learning outcomes of adopting this principle look like.

References

Acher, A., Arca, M., & Sanmarti, N. (2007). Modeling as a teaching learning process for understanding materials: A case study in primary education. *Science Education, 91,* 398–418.

Adadan, E., Irving, K. E., & Trundle, K. C. (2009). Impacts of multi-representational instruction on high school students' conceptual understandings of the particulate nature of matter. *International Journal of Science Education, 31*(13), 1743–1775.

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). Dordrecht, The Netherlands: Springer.

Bailer-Jones, D. M. (2002). Scientists' thoughts on scientific models. *Perspectives on Science, 10*(3), 275–301.

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

Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models for science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 41–57). Dordrecht, The Netherlands: Kluwer Academic.

Buckley, B. C. (2000). Interactive multimedia and model-based learning in biology. *International Journal of Science Education, 22*(9), 895–935.

Buckley, B. C., & Boulter, C. J. (2000). Investigating the role of representations and expressed models in building mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 119–135). Dordrecht, The Netherlands: Kluwer Academic.

Carmichael, P. (2000). Computers and the development of mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 177–189). Dordrecht, The Netherlands: Kluwer Academic.

Chevallard, Y. (1988, August). *On didactic transposition theory: Some introductory notes.* Paper presented at the International Symposium on Research and Development in Mathematics Education, Bratislava, Czechoslovakia.

Clement, J. J. (1989). Learning via model construction and criticism: Protocol evidence on sources of creativity in science. In J. A. Glover, R. R. Ronning, & C. R. Reynolds (Eds.), *Handbook of creativity: Assessment, theory and research* (pp. 341–381). New York: Plenum Press.

Clement, J. J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education, 22*(9), 1041–1053.

Clement, J. J. (2008). *Creative model construction in scientists and students: The role of imagery, analogy, and mental simulation.* Dordrecht, The Netherlands: Springer.

Clement, J. J., & Rea-Ramirez, M. A. (2008). *Model-based learning and instruction in science.* Dordrecht, The Netherlands: Springer.

Clement, J. J., Zietsman, A., & Monaghan, J. (2005). Imagery in science learning in students and experts. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 169–184). Dordrecht, The Netherlands: Springer.

Dunbar, K. (1999). How scientists build models in vivo science as a window on the scientific mind. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 85–99). New York: Kluwer Academic/Plenum Press.

Erduran, S., & Duschl, R. A. (2004). Interdisciplinary characterizations of models and the nature of chemical knowledge in the classroom. *Studies in Science Education, 40,* 105–138.

Gentner, D. (2002). Analogy in scientific discovery: The case of Johannes Kepler. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 21–39). New York: Kluwer Academic/Plenum Press.

Giere, R. N. (1988). *Explaining science: A cognitive approach.* Chicago: University of Chicago Press.

Giere, R. N. (1999a). *Science without laws.* Chicago: University of Chicago Press.

Giere, R. N. (1999b). Using models to represent reality. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 41–57). New York: Kluwer Academic/Plenum Press.

Giere, R. N., Bickle, J., & Mauldin, R. F. (Eds.) (2006). *Understanding scientific reasoning* (5th ed.). Toronto: Thomson Wadsworth.

Gilbert, J. K. (2005a). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9–27). Dordrecht, The Netherlands: Springer.

Gilbert, J. K. (Ed.) (2005b). *Visualization in science education.* Dordrecht, The Netherlands: Springer.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). Dordrecht, The Netherlands: Springer.

Gilbert, J. K., & Boulter, C. J. (Eds.) (2000). *Developing models in science education.* Dordrecht, The Netherlands: Kluwer Academic.

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3–17). Dordrecht, The Netherlands: Kluwer Academic.

Gilbert, J. K., Boulter, C., & Rutherford, M. (1998). Models in explanations. Part 1: Horses for courses? *International Journal of Science Education, 20*(1), 83–97.

Gilbert, J. K., Reiner, M., & Nakhleh, M. (Eds.) (2008). *Visualization: Theory and practice in science education.* Dordrecht, The Netherlands: Springer.

Gilbert, S. W., & Ireton, S. W. (2003). *Understanding models in earth and space science.* Arlington, VA: NSTA Press.

Gobert, J. D. (2000). A typology of causal models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education, 22*(9), 937–977.

Gobert, J. D., & Clement, J. J. (1999). Student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36*(1), 39–53.

Gobert, J. D., & Pallant, A. (2004). Fostering students' epistemologies of models via authentic model-based tasks. *Journal of Science Education and Technology, 13*(1), 7–22.

Gobert, J., Snyder, J., & Houghton, C. (2002, April 1–15). *The influence of students' understanding on model-based reasoning.* Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LO, USA.

Grandy, R. (2003). What are models and why do we need them? *Science & Education, 12,* 773–777.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799–822.

Guthrie, R. D. (1984). Mosaics, allelochemics and nutrients: An ecological theory of late Pleistocene megafaunal extinctions. In P. S. Martin & R. G. Klein (Eds.), *Quaternary extinctions: A prehistoric revolution* (pp. 259–298). Tucson: University of Arizona Press.

Halloun, I. A. (2004). *Modeling theory in science education.* Dordrecht, The Netherlands: Kluwer Academic.

Halloun, I. A. (2007). Mediated modeling in science education. *Science & Education, 16,* 653–697.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education, 22*(9), 1011–1026.

Hempel, C. G. (1965). *Aspects of scientific explanation and other essays in the philosophy of science.* New York: Free Press.

Henze, I., van Driel, J. H., & Verloop, N. (2007). Science teachers' knowledge about teaching models and modelling in the context of a new syllabus on public understanding of science. *Research in Science Education, 37,* 99–122.

Izquierdo-Aymerich, M., & Aduriz-Bravo, A. (2003). Epistemological foundations of school science. *Science & Education, 12,* 27–43.

Johnson, S. K., & Stewart, J. (2002). Revising and assessing explanatory models in a high school genetics class: A comparison of unsuccessful and successful performance. *Science Education, 86,* 463–480.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness.* Cambridge: Cambridge University Press.

Justi, R., & Gilbert, J. K. (2002a). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369–387.

Justi, R., & Gilbert, J. K. (2002b). Science teachers' knowledge about and attitudes towards the use of models and modelling in learning science. *International Journal of Science Education, 24*(12), 1273–1292.

Justi, R., & Gilbert, J. K. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*(11), 1369–1386.

Kemmis, S., & McTaggart, R. (1988). *The action research planner* (3rd ed.). Victoria, Australia: Deakin University Press.

Khan, S. (2007). Model-based inquiries in chemistry. *Science Education, 91,* 877–905.

Koponen, I. T. (2007). Models and modelling in physics education: A critical re-analysis of philosophical underpinnings and suggestions for revisions. *Science & Education, 16,* 751–773.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 121–146). Dordrecht, The Netherlands: Springer.

Lemke, J. (1998). Multiplying meaning: Visual and verbal semiotics in scientific text. In J. R. Martin & R. Veel (Eds.), *Reading science: Critical and functional perspectives on discourse of science* (pp. 87–113). New York: Routledge.

Losee, J. (2001). *A historical introduction to the philosophy of science* (4th ed.). Oxford: Oxford University Press.

Magnani, L., & Nersessian, N. J. (Eds.) (2002). *Model-based reasoning: Science, technology, values.* New York: Kluwer Academic/Plenum Press.

Magnani, L., Nersessian, N. J., & Thagard, P. (Eds.) (1999). *Model-based reasoning in scientific discovery.* New York: Kluwer Academic/Plenum Press.

Maia, P. F., & Justi, R. (2009). Learning of chemical equilibrium through modelling-based teaching. *International Journal of Science Education, 31*(5), 603–630.

Marquez, C., Izquierdo, M., & Espinet, M. (2006). Multimodal science teachers' discourse in modeling the water cycle. *Science Education, 90,* 202–226.

Martin, P. S. (1984). Prehistoric overkill: The global model. In P. S. Martin & R. G. Klein (Eds.), *Quaternary extinctions: A prehistoric revolution* (pp. 354–403). Tucson: University of Arizona Press.

Michalchik, V., Rosenquist, A., Kozma, R., Kreikemeier, P., & Schank, P. (2008). Representational resources for constructing shared understanding in the high school chemistry classroom. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 233–282). Dordrecht, The Netherlands: Springer.

Miller, P. H. (2001). Developmental issues in model-based reasoning during childhood. *Mind & Society, 4*(2), 49–58.

Morgan, M. S. (2002). Model experiments and models in experiments. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 41–58). New York: Kluwer Academic/Plenum Press.

Morrison, M., & Morgan, M. S. (1999). Models as mediating instruments. In M. S. Morgan & M. Morrison (Eds.), *Models as mediators: Perspectives on natural and social science* (pp. 10–37). Cambridge: Cambridge University Press.

Nakhleh, M. B., & Postek, B. (2008). Learning chemistry using multiple external representations. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 209–231). Dordrecht, The Netherlands: Springer.

National Research Council (NRC) (1996). *National Science Education Standards.* Washington, DC: National Academy Press.

Nersessian, N. J. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. N. Giere (Ed.), *Cognitive models of science* (pp. 3–44). Minneapolis: University of Minnesota Press.

Nersessian, N. J. (1999). Model-based reasoning in conceptual change. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 5–22). New York: Kluwer Academic/Plenum Press.

Nersessian, N. J. (2002). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal (Eds.), *The cognitive basis of science* (pp. 133–153). Cambridge: Cambridge University Press.

Oreskes, N. (2003). The role of quantitative models in science. In C. D. Canham, J. J. Cole, & W. K. Lauenroth (Eds.), *Models in ecosystem science* (pp. 13–31). Princeton, NJ: Princeton University Press.

Oversby, J. (2000). Models in explanations of chemistry: The case of acidity. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 227–251). Dordrecht, The Netherlands: Kluwer Academic.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching, 39*(3), 185–204.

Ramadas, J. (2009). Visual and spatial modes in science learning. *International Journal of Science Education, 31*(3), 301–318.

Rapp, D. N., & Kurby, C. A. (2008). The 'ins' and 'outs' of learning: Internal representations and external visualization. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). Dordrecht, The Netherlands: Springer.

Reiner, M., & Gilbert, J. (2008). When an image turns into knowledge: The role of visualization in thought experimentation. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 295–309). Dordrecht, The Netherlands: Springer.

Reynolds, S. J., Johnson, J. K., Piburn, M. D., Leedy, D. E., Coyan, J. A., & Busch, M. M. (2005). Visualization in undergraduate geology courses. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 253–266). Dordrecht, The Netherlands: Springer.

Rogers, Y. (2008). Using external visualizations to extend and integrate learning in mobile and classroom settings. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 89–102). Dordrecht, The Netherlands: Springer.

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2006). Effect of bead and illustration models on high school students' achievement in molecular genetics. *Journal of Research in Science Teaching, 43*(5), 500–529.

Rowley-Jolivet, E. (2004). Different visions, different visuals: A social semiotic analysis of field-specific visual composition in scientific conference presentations. *Visual Communication, 3,* 145–175.

Russell, J., & Kozma, R. (2005). Assessing learning from the use of multimedia chemical visualization software. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 299–332). Dordrecht, The Netherlands: Springer.

Rutherford, M. (2000). Models in the experiments of physics: The case of light. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 253–269). Dordrecht, The Netherlands: Kluwer Academic.

Schwarz, C. V., & Gwekwerere, Y. N. (2007). Using a guided inquiry and modeling instructional framework (EIMA) to support preservice K-8 science teaching. *Science Education, 91,* 158–186.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., … Krajcik, J. (2009). Developing learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632–654.

Schwarz, C. V., & White, B. Y. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*(2), 165–205.

Shen, J., & Confrey, J. (2007). From conceptual change to transformative modeling: A case study of an elementary teacher in learning astronomy. *Science Education, 91,* 948–966.

Smit, J. J. A., & Finegold, M. (1995). Models in physics: Perceptions held by final-year prospective physical science teachers studying at South African universities. *International Journal of Science Education, 17*(5), 621–634.

Snyder, J. L. (2000). An investigation of the knowledge structures of experts, intermediates and novices in physics. *International Journal of Science Education, 22*(9), 979–992.

Stewart, J., Hafner, R., Johnson, S., & Finkel, E. (1992). Science as model building: Computers and high-school genetics. *Educational Psychologist, 27*(3), 317–336.

Suarez, M. (1999). Theories, models, and representations. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 75–99). New York: Kluwer Academic/Plenum Press.

Suppe, F. (1972). What's wrong with the received view on the structure of scientific theories? *Philosophy of Science, 39,* 1–19.

Tsui, C.-Y., & Treagust, D. F. (2003). Genetics reasoning with multiple external representations. *Research in Science Education, 33*(1), 111–135.

van der Valk, T., van Driel, J. H., & de Vos, W. (2007). Common characteristics of models in present-day scientific practice. *Research in Science Education, 37,* 469–488.

Van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modelling in science. *International Journal of Science Education, 21*(11), 1141–1153.

Van Driel, J. H., & Verloop, N. (2002). Experienced teachers' knowledge of teaching and learning of models and modelling in science education. *International Journal of Science Education, 24*(2), 1255–1272.

Van Joolingen, W. (2004, August 30–September 1). *Roles of modeling in inquiry learning.* Paper presented at the IEEE International Conference on Advanced Learning Technologies, Joensuu, Finland.

Vosniadou, S. (2002). Mental models in conceptual development. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 353–368). New York: Kluwer Academic/Plenum Press.

Windschitl, M., & Thompson, J. (2006). Transcending simple forms of school science investigation: The impact of preservice instruction on teachers' understanding of model-based inquiry. *American Educational Research Journal, 43*(4), 783–835.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigation. *Science Education, 92,* 941–967.

Wynne, C. F., Stewart, J., & Passmore, C. (2001). High school students' use of meiosis when solving realistic genetics problems. *International Journal of Science Education, 23*(5), 501–515.