Myint Swe Khine
Issa M. Saleh
Editors

MODELS AND MODELING IN SCIENCE EDUCATION

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Cognitive Tools for Scientific Enquiry

Springer

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Volume 6

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ISBN 978-94-007-0448-0 e-ISBN 978-94-007-0449-7
DOI 10.1007/978-94-007-0449-7
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011921255

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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Part I
Theory Formation and Modeling in Science Education

Chapter 1
Modeling and the Future of Science Learning

Richard K. Coll and Denis Lajium

Introduction

Models and modeling are of such importance in science that the appropriate understanding of, and ability to use, models is seen by many authors as central to an understanding of science (Gilbert & Boulter, 1998; Harrison & Treagust, 2000; Ramadas, 2009). In this chapter we consider key aspects of models and modeling. We begin by describing the nature of models and modeling. We then discuss how models and modeling relate to the nature of science and scientific enquiry. This followed by a description of modeling as a cognitive tool and consideration of how models and modeling relate to the learning of science. We conclude the chapter by highlighting the areas of needed research in science education with respect to models and modeling.

The Nature of Models and Modeling

Three principal purposes for modeling in the sciences are reported in the science education literature: (1) to produce simpler forms of objects or concepts; (2) to provide stimulation for learning or concept generation, and thereby support the visualization of some phenomenon; and (3) to provide explanations for scientific phenomena (Gilbert & Rutherford, 1998a, 1998b; Passmore & Stewart, 2002; Ramadas, 2009; Thomas & McRobbie, 2001). The process of modeling involves the transfer of some features of the source of the model to the target of the model (Brodie et al., 1994) (Fig. 1.1). We thus have a target, something we want to understand; a source, something known to us from our everyday life or prior experiences; and the model which helps us bridge between the two (Brodie et al., 1994; Suckling, Suckling, & Suckling, 1978).

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_1,

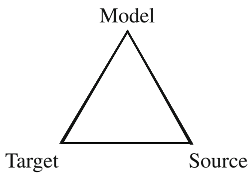

Fig. 1.1 The relationship between a model, its source and target (after Brodie et al., 1994)

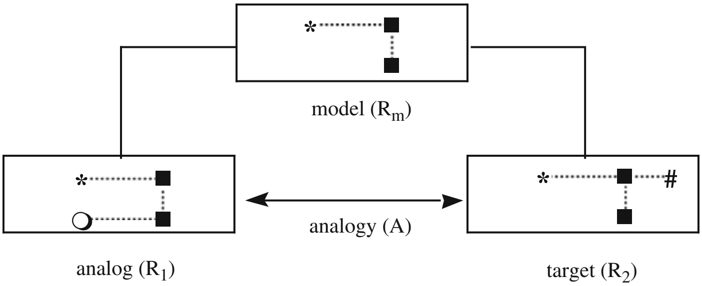

Fig. 1.2 Analogical transfer by structural mapping between two domains (from Duit, 1991)

A useful visualization of such mapping from target to source is provided by Duit (1991) (Fig. 1.2). In Duit's representation, the process of modeling involves analogical mapping—many authors believe that all models are in fact analogies and that all modeling consist of mapping via the use of analogy (A) (see, e.g., Gilbert, 2004; Harrison, 2008). In this mapping, there are features in parts of the structures of the analog (R_1) and target (R_2) that are shared (R_m).

From Fig. 1.2 it can be seen that modeling involves simplification of the target. In other words, the model is a simpler version of the target and shares only some attributes with the target (i.e., R_m). As a consequence, the extent to which the target and source share attributes varies (Maksic, 1990), and because of this the model and target may in some cases be very different and may be different in numerous ways. This is an inherent feature of models and modeling and should not be seen as some sort of flaw or limitation of models; indeed as we shall see it is a key component of models and modeling. The fact that the model is simpler than the target means is in fact beneficial, because we can ignore less relevant or unimportant details, and instead focus on the most interesting or important facets—selected and dominant features that help us understand key attributes of the target. Consequently, the use of a model enables scientists to identify key aspects of the target without becoming distracted by unimportant detail or attributes (Gilbert & Boulter, 1998). The initial grasping or generation of an abstract concept is more readily achieved when the concept has been stripped to the bare necessities required for understanding—a process of what Weller (1970, p. 118) describes as providing "a basic outline of the 'forest'."

So the nature of the target and the purpose of models, and subsequent modeling, vary, and so the models themselves vary considerably (Gilbert & Osborne, 1980).

Some are quite simple such as a two-dimensional drawing or a ball-and-stick model used to illustrate aspects of molecular geometry in a small molecule. Others are highly complex and might, for example, be used to provide detailed predictions of physical or chemical properties (e.g., quantum mechanical modeling of atomic structure, modeling of spectroscopic data such as nuclear magnetic resonance—NMR).

Although many authors emphasize the importance of models in science, there is much variation in the use of the terms model and modeling, and as a consequence numerous typologies of models have been developed. Examples of types identified in the literature include *knowledge models scale models target systems mental models*, and *expressed models* (see, e.g., Brodie et al., 1994; Gilbert & Boulter, 1998; Harrison & Treagust, 1998; Justi & Gilbert, 1999; Smit & Finegold, 1995; Suckling et al., 1978). These typologies can, however, be distilled down to a few key types. These are *target models*—the concept or phenomena of interest— and the *user's model*—the model possessed or used by an individual, often a mental model (Norman, 1983). A users' mental model is a personal mental construct and, according to radical constructivists, such a model is only accessible by another up to a point (Gilbert, 2004; von Glasersfeld, 1993). When users' models or mental models are shared and aspects of these are agreed they become *consensual models* (and after time an *historical model,* see Gericke & Hagberg, 2007). A consensus or historical model is a model that has been subject to some form of "testing" (e.g., physical testing or argumentation) by a particular social group. In the case of science this group is the scientific community, and this group or community agrees on the attributes and value of the model. *Teaching models*, as the name implies, are models using during instruction. *Expressed models* are models as they are expressed, or communicated, to others. This may take the form of actual expression (e.g., in language or drawings), or as one can interpret the model from analysis of presented models (e.g., in textbooks or scientific writing). This notion recognizes a model as the construct of an individual, or a particular community of practice, consistent with the view that any model is a mental model (Gilbert, 2004), and thus a personal mental construct (von Glasersfeld, 1993).

The above description of the nature of models is driven by the *purpose* or use of the model. Models also may be classified on the basis of the *nature* of the model. Obvious examples are *physical models* and *mental models*; but there also are numerous other types of models identified in the science education literature. Interestingly, the model typologies based on model nature or type throw up some things that we may not have thought of as models, for example, chemical equations. But if one considers the nature of models (viz, they are a representation of an entity or phenomena), then such classification is logical and appropriate. Again, classification schemes can be summarized in broad terms. So models have been classified on the basis of their nature as falling into two broad types *physical models* and *conceptual/symbolic models* (Brunner, 1967; Coll, 1999; Suckling et al., 1978). Physical models include things such as concrete physical models such as scale models used in engineering design or architecture and ball-and-stick or space-filling models used in chemistry (Black, 1962; Harré, 1970; Smit & Finegold, 1995; Tomasi, 1988).

Conceptual models consist of diagrams such as reaction schemes and metabolic pathways (Gilbert, 2004; Harrison & Treagust, 1996), and formulae (Gilbert, 2004; Harrison & Treagust, 1996; Trindle, 1984). Some models, like analog models, may be physical or conceptual/symbolic (Black, 1962; Duit, 1991; Peierls, 1980; Tomasi, 1988). Conceptual/symbolic models represent mental constructs; in other words, they are mental models (Brunner, 1967; Suckling et al., 1978) or expressed mental models (Gilbert, 2004).

Models, Modeling, and the Nature of Science

Here we delve into the nature of models and modeling in a little more detail, and consider how this relates to the nature of science. As noted above models possess a number of fundamental properties, a key feature being that they are human inventions or (mental) constructions. As such, they represent an approximation of reality (Portides, 2007), or a limited "version" of the target, and inevitably present an incomplete understanding of the entity or phenomena (Carr & Oxenham, 1985; Ganguly, 1995; Greca & Moreira, 1997). We might say they are "wrong" or "limited" in some key aspect (Tomasi, 1988; Trindle, 1984). Here, we mean they are *inherently* limited, because human understanding can never match reality (Harding & Hare, 2000). But many models possess notable limitations that are clearly recognized in advance, and these limitations may be unhelpful in the use or function of the model. Two examples illustrate our meaning here. First is the Aufbau principle used to explain the electron configuration of the elements. It is well recognized that many elements do not agree with predictions of the Aufbau principle (e.g., chromium and copper). But it "works" for most elements, so it is retained, and explanations are developed for the anomalous elements (e.g., inter-electron repulsion, Zumdahl & Zumdahl, 2003). Perhaps a more dramatic example is ligand field theory. Ligand field theory models bonding in organometallic complexes and is based on simple electrostatic attraction between a metal center and electron-rich ligands (atoms, ions, or groups) that surround it. This attraction leads to perturbation of energy levels for the metal *d* orbitals in particular, and the model allows for predictions of electron distribution and bonding. A major use of model is in the interpretation of electronic absorption spectra in the UV–visible portion of the electromagnetic spectrum. However, there is much evidence to suggest that ligand field theory fails in many ways; the simplest example relates to the failure of ligand field theory to explain the spectrochemical series. Interestingly, despite these obvious, and fairly serious, limitations, ligand field theory is still widely used by modern scientists (see, e.g., Nakamoto, 2009); simply because in many instances it is able to correlate some experimental data adequately, and it is therefore useful in some circumstances.

What is of particular interest here, to our discussion of the nature of science, is that even when models like ligand field theory possess severe limitations this does not necessarily mean that they are automatically discarded—particularly if not easily replaced (students often think once a model fails, it is discarded, see Shen &

Confrey, 2010). It is this highly pragmatic use of models that are known to possess quite significant limitations that distinguishes scientists from students (Shen & Confrey, 2010; Williamson & Abraham, 1995). Hence, a key aspect of the nature of science, as it pertains to models and modeling, is that scientists understand the nature of models and see models in a very functional, utilitarian, manner (Portides, 2007). They instinctively, or as a result of their training, recognize that *models are intended to serve the user* and frequently require modification (e.g., when new experimental data are obtained, see Borges & Gilbert, 1999). Grosslight, Unger, Jay, and Smith (1991) observe that one reason for this difference between scientists and students is that students and non-scientists tend to think of models in concrete terms, effectively as scale models of reality (see also, Abell & Roth, 1992; Bent, 1984b; Carr, 1984; Clement, 1998), and thus do not appreciate their limitations (Ogan-Bekiroglu, 2007). This, it is argued, occurs because some well-known models have proven spectacularly successful. Examples include the Watson–Crick model for the structure of DNA (Rodley & Reanny, 1977; Watson & Crick, 1953), Einstein's relativity (Clark, 1973; Kline, 1985), and Schrödinger's wave-mechanical model of the atom (Kline, 1985; Moore, 1989). What this may mean is that successful models are so powerful at explaining well-understood observationsthat they end up being regarded as "facts" (Schrader, 1984). In other words, a student or novice may confuse a highly successful, well established, model with reality, or the target it is being used to model.

Another aspect of the nature of science and models is the fact that it is common for scientist to use multiple models to describe an entity (Flores-Camacho, Gallegos-Cázares, Garritz, & García-Franco, 2007) or explain phenomena/data (Barnea, Dori, & Finegold, 1995; Birk & Abbassain, 1996; Lin & Chiu, 2007). The use of multiple models is particularly prevalent in some sciences such as physics and chemistry, especially when it comes to developing an understanding of abstract microscopic concepts like atomic structure and chemical bonding (Brodie et al., 1994; Chiu, Chou, & Liu, 2002; Comba & Hambley, 1995; Eilam, 2004; Glynn & Duit, 1995; Lin & Chiu, 2007; Lopes & Costa, 2007). Again, as might be expected, there are significant differences in how scientists view and use multiple models (see, e.g., Clement, 1998; Flores-Camacho et al., 2007; Grosslight et al., 1991; Harrison & De Jong, 2005), with scientists again acting in a highly pragmatic fashion. As an illustration, there are numerous models for chemical bonding, and scientists use whichever model seems appropriate and convenient (Coll & Treagust, 2003a, 2003b). Consider reactions of aromatic chemical substances. Molecular orbital theory provides the most comprehensive explanation for the bonding in aromatics (viz, delocalization of electron density across the molecule), but scientists routinely use electron dot Lewis structure-type notations and formulae when presenting reaction schemes (Coll & Treagust, 2002a). Key here, again, is that the scientist retains in his or her mind an acute appreciation of the limitations that such simple models possess, and that there are often apparent "contradictions" between models (Flores-Camacho et al., 2007) because they are used for different purposes.

The final aspect of models related to the nature of science we wish to raise here is the success or otherwise of models. We have already noted that all models possess some limitations or fail in some way, that is, the very nature of the models and modeling. We also suggested above that scientists still use these models, in ways they find useful. Maksic (1990) makes an interesting point, noting that a good match between the predictions of a given model and experimental data indicates that a model is reliable and useful. But Maksic goes on to observe that this should not be taken to infer that complex and sophisticated quantitative models are necessarily superior to simpler qualitative counterparts. Simple qualitative models, despite their apparent "lack of accuracy" or lack of sophistication, possess considerable value in science, for example, in theory generation (Koponen, 2007). Likewise, constructing an analogical model allowed Maxwell to gain access to a systematic body of knowledge, consisting of a structure of causal and mathematical relationships, during the development of his famous equations (Nersessian, 1992; Franco, de Barros, Colinvaux, Krapas, Queiroz, & Alves, 1999).

Models and Modeling in Scientific Enquiry

The literature thus suggests that models and modeling are an important part of doing science and that models play a key role in scientific enquiry. Models can play a number of roles in scientific enquiry, and four distinct functions have been identified: *discovery development evaluation,* and *exposition* (Cosgrove, 1995; Holyoak & Thagard, 1996, 1997). Discovery occurs when model contributes to the formation or generation of a new knowledge or the formulation of a hypothesis (Ganguly, 1995; Johnson-Laird, 1989; Stavy & Tirosh, 1993). When a hypothesis or discovery has been made, the model may then be used to further its development—either from a theoretical or from an experimental perspective. As the model is developed, we need to test the model, and so models play an important role in the evaluation of a hypothesis, and in evaluating arguments for or against the hypothesis. Finally, models are commonly used for exposition, that is, they are used to explain hypotheses or theories to others.

Some authors argue that all models are analogy; whether one believes this or not, analogies are an important model type used for concept generation. Because such analogy or model use in concept generation is a personal mental process, it is difficult to document, although there are numerous scientific theories for which models clearly contributed to some vital stage of a scientists' thinking, whether it was in discovery or the development of an idea (as described above). There are a number of well-known models that clearly illustrate the role that models can play in concept generation during the development of scientific theories (Sutton, 1993). Holyoak and Thagard (1996) identified a number of models that they say have played a role in theory development (mostly analogies). Examples include the Kekulé's snakes biting their tails used to model the structure of benzene. Model use thus plays a generative role—mostly when in situations for which prior knowledge is weak or when there is little connection between ideas (Silva, 2007; Wong, 1993a, 1993b). The generative function here comes from the way we use models (see Duit's model described in Fig. 1.2 above), in that the scientist, trying to solve a problem or explain some data, engages in the mapping of attributes from the known to the unknown (Harrison, 2008; Wong, 1993a). In doing so, the analogy or model provides insights and inferences. As Wong sees it, these generative models are *dynamic* tools rather than *static* representations used for understanding. In such circumstances, individuals seek to find ways of making it easier to explain observed phenomena and so develop their own models to advance their understanding (see also, Johnson-Laird, 1989).

Justi and Gilbert (2002) analyzed how models are produced in science and developed a "model of modeling" (Fig. 1.3). This *model of modeling* exemplifies the

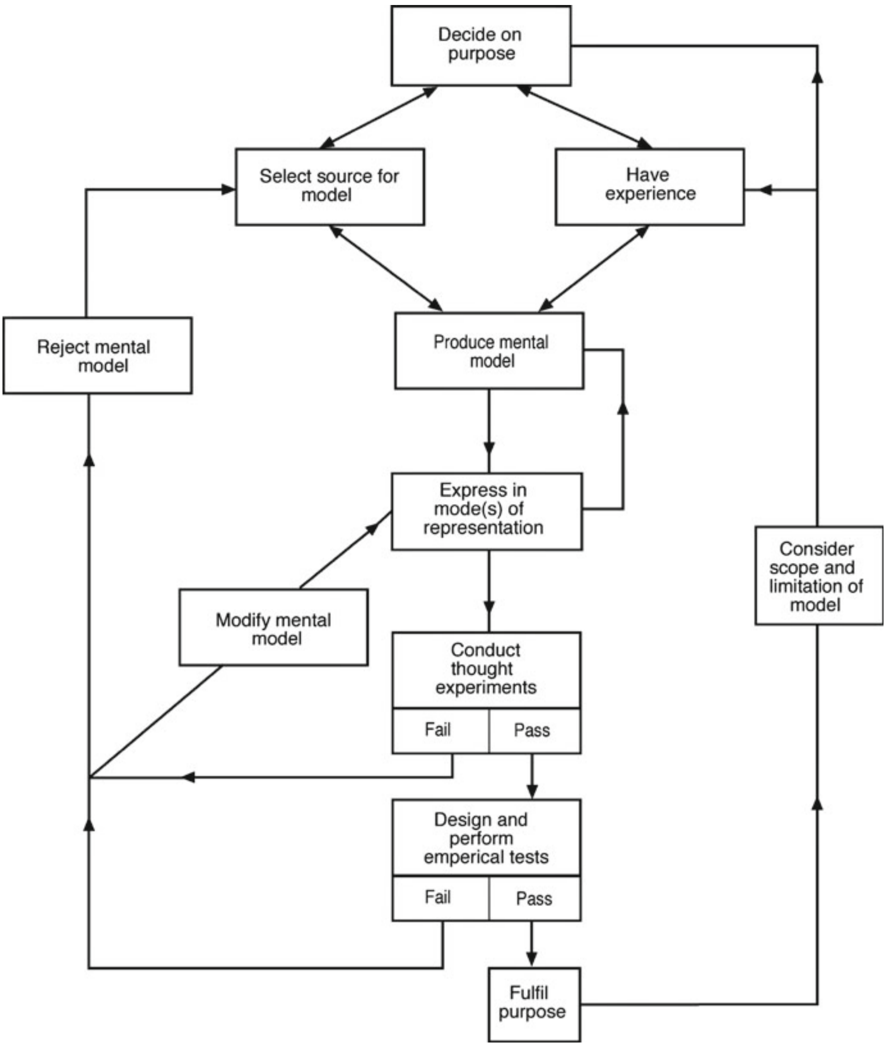

Fig. 1.3 A "model of modeling" (after Justi & Gilbert, 2002)

essential features of scientific modeling as used in scientific enquiry. Notable is the dynamism of the model (Maia & Justi, 2009), in that data are "reconsidered" constantly, and the relationship between data and the mental models developed by scientists to explain these data is examined in an on-going, iterative fashion. Considerable emphasis is placed on testing any scientific model and re-examination of relationships between data and models (as we might expect). Acceptance or rejection of a model is related to the purpose of the model, which remains paramount—consistent with the literature described above. Sins, Savelsbergh, van Joolingen, and van Hout-Wolters (2009) sum the use of models and modeling in scientific enquiry nicely, describing it as a process of developing, comparing, and testing competing models.

Modeling as a Cognitive Tool

The above discussion indicates that models, particularly analogical models, function as cognitive tools. The literature also suggests that students fail to appreciate that the principal function of mental models in science is to aid in the understanding of some phenomenon, as mentioned above. This lack of insight is highlighted in studies across different science disciplines. For example, studies by Grosslight et al. (1991); Abell and Roth (1992) in the biological sciences, Bent (1984b) in chemistry, and by Raghavan and Glaser (1995) in physics support this conclusion. Gabel, Briner, and Haines (1992) suggest that mismatch between scientists' and students' perceptions of the role of models may be due to the inability of novices to operate at the formal level. To illustrate, chemistry can be described on three distinct levels, sensory, atomic/molecular, and symbolic. Usually a chemical substance is represented on the atomic/molecular level using models such as three-dimensional representations (Ke, Monk, & Duschl, 2005). However, students typically attempt to address chemical problems on one level alone, for example, using a purely symbolic approach (Jansoon, Somsook, & Coll, 2008, Jansoon, Coll, & Somsook, 2009; Tan et al., 2008). Consequently, some authors argue that it is essential for instructors to design problem-solving exercises that utilize all three levels in an integrated manner to foster genuine understanding, as opposed to merely achieving competence in the use of algorithms (Gabel et al., 1992; Green, 1996; Jansoon et al., 2008, 2009; Nakhleh, Lowrey, & Mitchell, 1996; Pestel, 1993), or to involve students in concrete sensori-motor experiences (Ke et al., 2005) that provide a range of experiences that develop p-prims that can be incorporated into their schema.

Given the complexity of some specific models, the huge variety of models, and the issues associated with model use, it is not surprising that many authors regard the appropriate use of models as a complex task. Bent (1984a) makes parallels between learning chemistry via models and learning a language. Hence, the literature recommends that science teachers introduce a model only when necessary to explain an experiment or an observation (Coll, France, & Taylor, 2005; Harrison & Coll, 2008). Students appreciate more about how scientists actually use models when led through an enquiry type sequence. For example, they may be taught Lewis structures and the octet rule and subsequently confronted with “problematic” molecules like molecular oxygen or nitrogen (II) oxide, which require new, more sophisticated models with greater explanatory power (Gilbert, 2004)—such as molecular orbital theory (Coll & Treagust, 2002a). There also are indications in the literature as to specific aspects of modeling students find difficult. One issue is using and interpreting two-dimensional models, where students need to understand and respond appropriately to visual diagrammatic clues (Baker & Talley, 1972; Mathewson, 1999; Pribyl & Bodner, 1987; Ramadas, 2009; Small & Morton, 1983; Wartofsky, 1979; Weller, 1970). Alternative conceptions can easily be generated by diagrams (Coll & Taylor, 2001), because the diagrams quite deliberately highlight particular features (as noted above, this is a key purpose of modeling, see Head, Bucat, Mocerino, & Treagust, 2005). The resultant “exaggeration” of these features, done to highlight what the presenter is retying to convey, often confuses students. As an illustration, Coll and Treagust (2003) note that even senior level university students retain realistic images of atoms, as a result of exposure to realistic-looking diagrams—something Taber and Coll (2002) ascribe to an atomistic view of the structure of matter (i.e., students think everything is composed of individual atoms, ignoring molecules, covalent/ionic networks). Likewise, Fazio et al. (2008) talk of students relating to models associated with “events,” and Lin and Chiu (2007) comment that students adhere to what they term a “phenomenon model” where, for example, their mental model of an acid is related to some phenomenon associated with its nature or use (e.g., an acid is corrosive; metals are hard). However, students’ ability to better visualize models can be enhanced even after rudimentary training (Coleman & Gotch, 1998; Tuckey, Selvaratnam, & Bradley, 1991). Wheeler and Hill (1990), for example, note that the likelihood of inaccurate interpretation can be much reduced by getting students to draw their own diagrams, and working with them to be more critical of diagrams in textbooks and other curriculum material, something also noted by Coll and Treagust (2005). Gilbert (2004) expands on this, arguing that we need to get students to both develop and *revise* their own models. The use of models as cognitive tools like this may help students better understand the nature of models and the modeling process (Ünal, Çalik, Alipaşa, & Coll, 2006). Hansen, Barnett, MaKinster, and Keating (2004) say that three-dimensional computer modeling in particular can aid students’ understanding of spatially oriented concepts—something supported by Piburn et al. (2005). However, Sins, Savelsbergh, and van Joolimngen (2005) observe that even when teaching using computer-based modeling, we need to provide scaffolding, for example, involving the use of exemplars for modeling, and Louca and Zacharia (2008) say that the nature of the program used to deliver the CAI also influences modeling behavior of students (e.g., software that encourages conversations and argumentation about models and modeling). It does seem that a key issue in students’ ability to utilize modeling as a cognitive tool is their epistemology of models and modeling (Develaki, 2007; Matthews, 2007). Students with a sound epistemology of modeling (viz, like that of a scientist, see Grosslight et al., 1991) are apparently more likely to engage in deep, versus surface, processing of knowledge (Sins et al., 2009).

Modeling in the Teaching and Learning of Science

The previous section highlighted the role models can play as cognitive tools. It was noted that students struggle to understand models and to engage in modeling in the way scientists do. Here we consider what the literature has to say about models, modeling, and the learning of science. Van Driel and Verloop (2002) suggest that there are two key features of teaching models and modeling. First is an observation that teachers tend to focus on teaching-specific models, rather than modeling per se. In particular, they focus on the *content* of scientific or teaching models. This means that they do not communicate much about the nature of scientific modeling. Second, teachers need a better understanding of their students' own models (Gilbert, 2004) and ideas about modeling. Justi and Gilbert (2003) comment that modeling as an activity for students, while ostensibly valued by teachers, seldom is actually practiced in the classroom. In other words, teachers may genuinely appreciate the value of models in science, but this may not manifest in science teaching. The teaching of models in classrooms is complex and problematic, necessitating purpose-designed pedagogies, appropriate to the content (Taylor et al., 2003). Indeed, this is also for learning outside the classroom (see Falcão et al., 2004). Taylor et al. go on to say that if done well this makes models and modeling accessible to young students, even as young as year/grade 7–8, something supported by Besson and Viennot (2004) and Kawasaki et al. (2004). However, Saari and Viiri (2003) caution that improvements in student modeling capability may be temporary, unless modeling is incorporated into normal teaching (i.e., rather than relying just on model-based teaching interventions). Kawasaki et al. (2004) support this and argue that the early years of science education are crucial because here we have an opportunity to introduce students to "socioscientific norms," because we can build on their natural curiosity at this age. This then allows us to begin the process of helping students to develop an appreciation of a key aspect of the nature of science and scientific enquiry at an early age, an age when crucial attitudes toward science are first established (Dalgety, Coll, & Jones; Shen & Confrey, 2010).

Many researchers argue that confusion in students' use of models may have origins in the instruction itself (e.g., Fensham & Kass, 1988; Harrison & Treagust, 2000; Raghavan & Glaser, 1995). This could be due to confusion between physical models and reality as reported by Smit and Finegold (1995) and Matthews (2007) or inability to distinguish between a mental image and concrete model (Barnea et al., 1995). A complication for instructors in using models in science teaching is that sometimes the models used are attempting to model other models, a classic example being that models for the bonding in molecules and crystals are derived from models of atomic structure (Harrison & Treagust, 1996). Lack of communication about subtle but important aspects of models and modeling during instruction also can lead to confusion. For example, Weller (1970) suggests that confusion often arises because of "verbal shorthand" that is common among experts. In other words, the scientist or teacher is clear on what he or she means and when communicating with another like-minded expert no confusion arises. However, when the scientist is attempting to communicate with a novice or the general public, confusion between the model and the modeled arises because the scientist, fully realizing the difference between model and theory, may talk about the theory in terms of the model as if they were one and the same (Coll & Treagust, 2001, 2002a, 2002b, 2003a, 2003b; Harrison & Treagust, 1996; Pereira & Pestana, 1991; Taber & Coll, 2002).

Crawford and Cullin (2004) argue that many pre-service teachers themselves lack an understanding of models and modeling, making it unlikely that they can convey such knowledge to their students. This may arise from lack of understanding of scientific epistemology (Ke et al., 2005; Tsai & Liu, 2005), and another main factor is learning the language of modeling. A similar situation exists for in-service teachers (see Buty & Mortimenr, 2008; Henze, Van Driel, & Verloop, 2007). Each of these issues distills down to the same thing, understanding the *nature* and the *purpose* of models and modeling in science. Justi and Van Driel (2005) say to advance this agenda we need to have a sound understanding of pre-service teachers' pedagogical content knowledge (PCK) about models and modeling, so we can provide appropriate training (Halloun, 2007). We need to challenge them to analyze their practices and to involve them in training activities that closely resemble classroom practice. Sins et al. (2005) suggest that this necessitates scaffolding of learning (see above), something Oliva, Azcárate, and Navbarrete (2007) say needs constant monitoring by teachers (see also Lopes & Costa, 2007). However, Buty and Mortimenr (2008) sound a note of caution, reporting that even very experienced teachers, with a sound knowledge of models and modeling, can have difficulties in teaching models and modeling. This it seems occurs because of a lack of ability or framework for the communication of key features of the modeling process. Finally, Prins et al. (2009) observe that teaching students about modeling works best when the modeling used is "authentic." By this they mean that it involves relevant examples drawn from the students' worldviews and experiences (see also Halloun, 2007; Shepardson et al., 2007; Spiliotopoulou-Papantoniou, 2007; Wu, 2010). The idea is that once students understand modeling per se, they then are better able to understand how scientists use models and modeling in scientific enquiry (Wu, 2010), developing what is referred to in the literature as scientific habits of mind (Coll, Taylor, & Lay, 2009; Gauld, 2005).

We mentioned the use of multiple models above. Prain and Waldrip (2006) note that because of student difficulties in understanding multiple modes of representation, we need to provide training in this process. This is in accord with the views of Lopes and Costa (2007), who argue that the need for such training is "urgent." Multiple modes of representation, it is reported, work best if at least some of them are student generated (see Coll & Harrison, 2008). However, Harrison and De Jong (2005) suggest that if we do use multiple models in science teaching, we need to identify our rationale for doing so, and at the same time clearly elucidate the limitations of any models we introduce.

Future Work

There is now a substantial body of literature on models, modeling and issues to do with student understanding of models and modeling. So what do we know? First, there is good evidence or discussion in the literature about the nature and purpose of models and mental models, and how scientists use them in scientific enquiry. Crucial issues here are that (a) scientists understand that every model has some limitations; (b) scientists see models as cognitive tools that have a strong generative function (Silva, 2007), that is, they are important and valuable in developing new hypotheses and explaining data/phenomena; (c) scientists use models very pragmatically and do not automatically discard models even if they posses considerable limitations; and (d) when scientists use models that they know possess specific, or severe, limitations, they are aware of these limitations even as they use the models. Second, not surprisingly, students struggle to understand models and modeling in the same way scientist to. A potential issue here is that pre- and in-service teachers' understanding of models and modeling itself may be limited. On a positive note, there are a variety of interventions described in the literature reported to improve students' understanding of models and modeling. Key issues here are developing an appropriate epistemology of modeling and that modeling needs to be infused throughout the teaching process—much like the nature of science (Develaki, 2007; Gilbert, 2004; Matthews, 2007; Portides, 2007). The model of modeling proposed by Justi and Gilbert (2002) provides a useful framework for teaching modeling, and the typology employed by Grosslight et al. (1991) provides a nice evaluation tool, if seeking to understand how students use models including their models, or that proposed by Chi and Roscoe (2002), if seeking to understand their expressed mental models. Kozma and Russell (2005) sound caution that evaluation of student models may be influenced by their "representational competence," that is, their ability to properly represent/communicate their (mental) model. In terms of needed research, we suggest there are two main topics worthy of further work. First is a need to better understand the prevalence of pre- and in-service teachers' understanding of models and modeling. It is worrying that this is an issue, and we need to know just how much of an issue it is. If the issues about teachers' understanding and use of models and modeling identified in the literature are prevalent, we need research on how to remedy such problems (see Gilbert, 2004). Second, we need more classroom-based research about the teaching of modeling and across a greater variety of topics. The literature does contain some excellent studies, but these are almost entirely confined to chemistry and physics. We need better evidence as to how we should incorporate teaching about modeling in the biological and earth/space sciences. As a final thought, Gilbert (2004) argues for a model-based curriculum. Given that the literature indicates that models and modeling are a core feature of scientific enquiry this suggestion makes sense. If this does eventuate then plainly we need to develop appropriate evaluation of model-based teaching (including assessment of student understanding, curriculum evaluation, teacher appraisal).

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Chapter 2
A Study of Expert Theory Formation: The Role of Different Model Types and Domain Frameworks

Allan Collins

This study built upon earlier work (Collins & Ferguson, 1993; Morrison & Collins, 1995) I had carried out on "epistemic forms." These are recurring forms that are found among theories in science. Some of the different forms that occur are stage models, hierarchies, primitive elements (e.g., chemical elements), multi-factor models, constraint equations, axiom systems, agent models, trend analysis, and system-dynamics models. Some of these forms describe structures and some describe functional or causal relationships. Likewise, some of the forms are static and some are dynamic (i.e., process models). In the two previous papers, we described over 20 of these forms that are commonly found underlying scientific and historical theories.

Theory formation in different disciplines involves mastering how to carry out investigations of phenomena guided by one or more of these target structures. We refer to the set of rules and strategies that guide the construction of theories using different epistemic forms as "epistemic games." We call them epistemic games because of the parallel to games such as tic-tac-toe. The difference between forms and games is like the difference between the squares that are filled out in tic-tac-toe and the game itself. The game consists of rules, strategies, constraints, and different moves that players master over a period of time, as they learn to play the game. The squares form a target structure that is filled out as any particular game is played. In this view, scientific models are epistemic forms that have been filled in according to the rules of the epistemic games.

Creating Models

The different epistemic forms or model types are tools for making sense of the world. The structural forms are often the first forms people use to try to create a model. The simplest structural form is just a list, so that if you are trying to identify the variables that affect global temperature, you might start by creating a list of the

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_2,

causes or important factors governing climate, such as orbital variation, dust particles, and greenhouse gases. Stage models are a simple type of time-structured list, but they invoke additional constraints. The simplest stage model is a list constructed with the constraint that the stages follow each other sequentially without overlap (e.g., the hunter-gatherer age, the agricultural age, and industrial age). But it is possible to construct a more complicated version of a stage model, where, for example, trends are specified in each stage.

Multi-factor models are created by starting with a list of factors that are conjectured to affect a dependent variable. Then the goal is to create causal chains that link the different factors to the dependent variable. These causal chains are often configured in an AND/OR graph. Multi-factor models can be expanded into system-dynamics models by adding feedback loops between the different variables. Multi-factor models are particularly pervasive in geography, psychology, and medicine, but are common in many other disciplines where it is important to identify a pattern of variables that are causally interlinked.

In multi-factor models, variables (called factors or independent variables) are linked together in a tree structure, as in Fig. 2.1. The branches of the tree are ANDed together if a set of factors are all necessary to produce the desired value on the dependent variable. They are ORed together if any of the factors are sufficient to produce the desired value on the dependent variable. The figure shows an AND/OR graph that one respondent produced as his theory of what determines where rice is grown (Collins, Warnock, Aiello, & Miller, 1975). To grow rice the student stated that you need a warm temperature, fertile soil, and a supply of fresh water to flood a flat area. He further specified two ways to get a supply of fresh water and two ways to get a flat area. This epistemic form served as a target structure to guide his construction of his mini-theory about where rice can be grown.

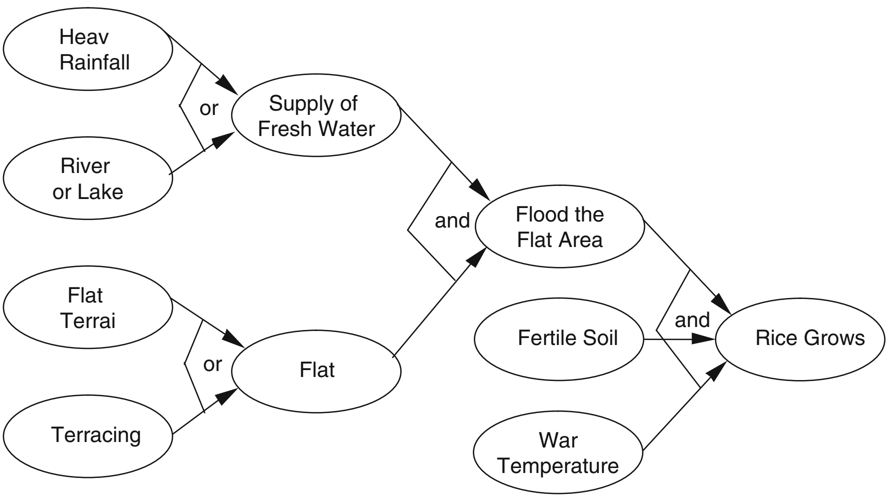

Fig. 2.1 A student's analysis of the causal factors affecting rice growing

These examples illustrate how epistemic forms guide the construction of models. There are a number of computer programs that have built-in epistemic forms that guide the construction of models. For example, Stella (Mandinach & Cline, 1994) guides the construction of system-dynamics models, and StarLogo or NetLogo (Wilensky & Reisman, 2006; Wilensky & Resnick, 1999) guides the construction of agent models or what Collins and Ferguson (1993) referred to as aggregate-behavior models.

This study sought to determine whether four expert researchers use these epistemic forms in constructing theories, how they are used if indeed they are used, and what other kinds of resources they bring to the task of theory construction. The findings indeed showed that the epistemic forms guide theory formation, but there are a variety of other epistemic resources that the experts use in constructing their theories.

A Protocol Study of Expert Theory Formation

In order to study theory formation I collected extended protocols from three scientists (a physicist, biologist, and psychologist) and a historian, as they addressed each of four questions that required problem solving and theorizing. The physicist is a well-known researcher with a Ph.D. in theoretical physics from New York University. The biologist is an active researcher with a Ph.D. in neurobiology and developmental genetics from Case Western Reserve University. The psychologist is a well-known researcher and professor with a Ph.D. in experimental psychology from the University of Michigan. The historian has a Ph.D. in American history from the University of California, San Diego, but has not been an active researcher or professor.

The subjects worked on four questions that required them to formulate theories, spending 2–3 h on each question. They recorded their thoughts as they went along into a tape recorder and on a legal-size pad of paper, whenever they felt it was appropriate. They did not record all their thoughts, only those that showed some progress in their thinking as they read the materials and worked out their ideas. Table 2.1 shows the instructions the subjects were given.

The four questions covered a range of topics in the biological, physical, and social sciences. They did not address the areas of inquiry for which any of the subjects had particular expertise. The questions were meant to require different kinds of solutions, such as predictions, explanations, policy decisions, and analysis of patterns in data. We provided the experts with a variety of scientific articles and books that they could study in order to formulate their own theories. The four questions were as follows:

- *What is the cause of declining wages in America and what should we do to reverse the decline*? This question was framed over the time period from the early 1970s to the mid-1990s. The materials consisted of five books with different views and explanations, ranging from economic to political to demographic approaches.

Table 2.1 Instructions for subjects

1. Your task is to analyze the problem given and come up with your own solution or theory to address the problem.
2. When you are finished analyzing the problem, we want you to write up your solution in some form, such as text, a figure, a table, or preferably a combination of these.
3. You will have 2–3 h to work or longer if you need the time, but you should try to finish in 2 h.
4. Spend as little time as possible for reading. Try to work through the problem using the materials as a reference.
5. Your job is to construct your own analysis of the problem. Do not give us the solutions or theories of the authors you are reading.
6. Bring in whatever knowledge you have from other sources. Try to identify what that knowledge is and its source.
7. Try to make integrative notes and representations of your thinking as you go along. The more detailed your notes, the better.
8. Explain your thinking as you go as thoroughly as possible into the tape recorder. You can pause the tape recorder while you read, so we do not get a lot of blank tape.
9. Try to write down and say what your current solution is as you go along, explaining why you think, what you do, and why you make any changes in your view.
10. If you change your mind about something, make a special effort to make note of the change and what caused it. It is not easy to remember you are changing your mind so please make a special effort to notice any change.
11. When you start generating a particular representation, try to say where it came from.
12. Do not feel that you need to read or even look at all the materials. Select those that interest you most and focus your investigation, however, you think is most productive.

- *How will the climate of the Earth change over the next 10–10,000 years*? *Please project the changes over the entire period.* The materials consisted of about 20 articles about climate changes discussing various change agents, such as carbon dioxide, dust particles, orbital variation, sunspot variation.
- *How do teenagers in different countries differ*? Subjects were given a book titled *The Teenage World* (Offer, Ostrov, Howard, & Atkinson, 1988) with a large data set from ten countries of teenagers' answers to about 100 psychosocial true/false questions, such as "My parents will be disappointed in me in the future." or "I enjoy most parties I go to." The data were separated by gender and age (younger = 13–15 years and older = 16–18 years). The text described the patterns the researchers identified in the data.
- *What do you predict for the world's resources and environment over the next 50 years? Make explicit predictions at least about food, energy, materials, pollution, and wildlife.* The materials consisted of several books and articles giving trend data, explanations for the trends, and future projections.

My analysis of the data collected from the experts was carried out by reading through transcripts and the subjects' notes looking for common elements in the subjects' approaches to the four problems. The categories that emerged were those that seemed particularly salient for the theory construction process and that might be teachable to students to make them better thinkers. In the analysis I identified five different epistemic elements: *epistemic strategies* (general-purpose analysis strategies), *epistemic forms* (target structures for the analysis), *epistemic concepts* (concepts to consider such as feedback loops or lag effects), *key variables* (variables that enter into different types of models), and *domain frameworks* (prior theoretical structures for guiding an analysis). Below I discuss each of these and the role they played in the protocols.

Epistemic Strategies. In addition to the epistemic games associated with different epistemic forms (Collins & Ferguson, 1993), the protocols show that there are also very general epistemic strategies that experts use, which are not tied to a particular epistemic form. The *theory-and-evidence game* discussed later in the chapter and in Morrison and Collins (1995) is an example of such a general-purpose epistemic strategy. The epistemic strategies that I identified in one or more protocols include the following:

- *Hypothesis formation and testing*. In the teenager problem the experts all generated hypotheses of the form: "Teenagers of type x have more/less of property p than teenagers of type y." (e.g., Teenagers in Japan and Taiwan are less happy than teenagers in western countries.) They then proceeded to look at all the questions relating to the property in question to see if the data supported their hypothesis. Similarly on the climate problem the psychologist conjectured that the effect of greenhouse gases on global temperature was greater than the effect of orbital variation, which has been driving the ice ages. So he went through the articles on climate trying to determine the relative size of the two effects in order to test his hypothesis.
- *Looking for and explaining anomalies.* The historian used a variation on the hypothesis testing strategy that is worth noting. In the teenager problem, she went through the data looking for cases (e.g., that Italian teens are less happy than teens in other rich countries) that did not fit the overall pattern she saw, in which poor countries had less happy teens than richer countries. Then she would often try to construct a causal chain or explanation that would account for the anomaly.
- *Identifying factors or key variables.* Much of the thinking and reading that the four experts did was directed toward identifying factors that might have an influence on the dependent variable in question (as can be seen in the protocol analyses shown in the next section). So, for instance, on the wages problem they tried to identify factors, such as women entering the work force, which might tend to drive down wages. This strategy supported the construction of causal chains, multi-factor models, and system-dynamics models.
- *Determining the effect of one variable on another.* In constructing their theories the three scientists tried to determine how one variable (or factor) affects another variable (the dependent variable). The physicist used this strategy to construct causal chains in order to verify that a factor he had identified would have the effect on the dependent variable that he thought it should have, as he constructed a multi-factor model. These causal chains were also used to support construction of a system-dynamics model and to counter weak links (see below).
- *Countering the weak links.* The wages problem called for proposing solutions to the problem of declining wages. One strategy the experts used was based on

identifying weak links in any causal chains linking factors to the dependent variable and then figuring out a way to counter those links. In the wages problem, this strategy involved identifying policy approaches that would interfere with any causal chain leading to declining wages.

- *Segmentation*. In several of the problems the three scientists would break a class of things or situations into subclasses and develop theories to deal with each of the subclasses. This strategy is what is known in logic as "proof by cases." For example the psychologist distinguished among developed countries and developing countries in making predictions about pollution growth.

Epistemic Forms. Epistemic forms are the target structures that guide researchers in their analysis. A large number of these forms are described in our earlier papers (Collins & Ferguson, 1993; Morrison & Collins, 1995). There was a progression of forms I noted in the protocols, where subjects would start working out causal chains, which they sometimes develop into multi-factor models. In one case the biologist extended his multi-factor model into a system-dynamics model. These are the target structures that I identified in the protocols:

- *Comparisons.* As we said above, all the experts in the teenager problem generated comparisons of the form: "Teenagers of type x have more/less of property p than teenagers of type y." These can be thought of as comparative rules of a more general form "X's have more of property P than Y's." They are a simplified form of the comparison tables discussed in the Collins and Ferguson (1993) paper.
- *Causal Chains.* As we mentioned above, the three scientists spent much of their time constructing causal chains, particularly as they tried to elaborate how a particular factor affected the dependent variable. The causal chains constructed had the following form: $a\uparrow \Rightarrow b\downarrow \Rightarrow c\uparrow$, where a, b, and c are variables that increase or decrease as specified by the respondent. The chains were of different lengths, but most contained two or three links.
- *Multi-factor Models*. In several of the problems the three scientists attempted to create a multi-factor causal model (Collins & Ferguson, 1993). For example, on the wages problem the physicist tried to identify all the factors that might lead to lower wages, such as women and baby boomers entering the work force, at the same time specifying the causal chains by which each would lead to lower wages.
- *Stage Models.* The psychologist created several stage models, where he broke a process down into two or more phases with different properties. In two cases he combined the stage model with trend analysis, in order to characterize how trends would unfold in different stages.
- *Trend Analysis.* One way that the three scientists made predictions was to project trends forward in time. The psychologist would often characterize the functions he expected to occur, such as linear, exponential, or asymptotic functions. Thus he was using standard functions in order to classify the behavior of the systems he was analyzing.
- *Finite-State Model.* The physicist in working on the wages problem created a simple two-state model, which is a special case of a finite-state model. The two stable

states he depicted were (1) high wages, women not working, family income = x, and (2) low wages, women working, family income = x’, where x and x’ are similar. He characterized recent decades as moving from state (1) to state (2), brought on by women entering the work force.

- *Systems-Dynamics Model.* The biologist in working on the resources problem created a systems-dynamics model, where he tried to incorporate all five of the variables (food supply, energy, materials, wildlife, and pollution) specified in the problem with six other variables (e.g., climate, technology, policies) in a complex interaction pattern, with multiple feedback loops.

Epistemic Concepts. The three scientists talked about processes and effects that were part of their toolkit for understanding the phenomena that they were dealing with, but that were less elaborated than the domain frameworks (see below) and more content specific than the epistemic forms. We have called these epistemic concepts, for want of a better name.

- *Lag effects.* The three scientists talked about lag effects or time delays in the two problems where predictions were called for. So, for example, in the resources and climate problems they refer to the time delays between when some event occurs (e.g., releasing carbon dioxide) and its full effects are felt (e.g., earth warming). Lag effects then are used to explain certain kinds of system dynamics.
- *Feedback loops.* There are two kinds of feedback loops that the scientists used in making sense of the problems, positive and negative feedback loops. The biologist referred to autocatalytic processes which are a special kind of positive feedback loop that occurs in biological processes, but there was also a positive feedback loop that the physicist noted in climate when snow leads to increased reflection of heat into the atmosphere, causing further cooling. Negative feedback occurs in many of their analyses when processes are self-limiting or people are motivated to counter certain effects.
- *Size of effects.* Another important notion that came up in several of the protocols is the relative size of different effects. For example, the psychologist spent a fair amount of time on the climate problem trying to determine the relative size of the effects of carbon dioxide and orbital variation.
- *Types of functions.* The psychologist was concerned in two of his protocols with the types of functions different processes produce. He discussed exponential functions, linear functions, and asymptotic functions. These were a set of epistemic tools he used to make sense of how different processes unfold.
- *Difference between the median and average.* The physicist in working on the wages problem spent time discussing how when inequality in wages increases, the average wage might increase while the median wage decreases. The difference between the median and average is a critical distinction in scientific reasoning.
- *Side effects vs. main effects.* The three scientists described certain effects as side effects, implying that the actions people were taking would lead to such effects,

even though they were not the intended effects. For example, the warming of the earth by greenhouse gases was treated as a side effect of burning fossil fuels.

Key Variables. All four experts identified key variables that they thought would affect the dependent variable in the question and worked from these key variables in building causal chains, multi-factor models, or in one case a system-dynamics model. These are concepts like orbital variation in climatology or labor supply in economics. For example, the physicist spent time on the declining wages problem trying to figure out what variables might have increased the labor supply, thus driving down wages. He came up with variables such as "the increase of women in the work force" and "the increase of baby boomers in the work force." These key variables function as the building blocks in any type of theory they develop. We will give three examples of key variables which different subjects used.

- *Technology.* The physicist developed an elaborate argument as to how introduction of technology would lead to falling wages. His argument was basically that technological refinement leads to the same amount of goods being produced by fewer people, which leads in turn to less demand for labor and hence lower wages.
- *Labor supply, etc.* The scientists referred to the key variables of labor supply, labor demand, supply of goods, and demand for goods, in working through the declining wages problem. These are variables that come out of the supply and demand framework that the experts used to organize their analysis of the problem. These are what are referred to in the literature as "intermediate variables."
- *Greenhouse effect, etc.* All of the subjects, as they worked on the climate problem, identified a number of controlling variables. The greenhouse effect and orbital variation were the largest of these variables. The psychologist saw his first task as identifying all of the key variables that affect climate and then determining which had the greatest effect.

Domain Frameworks. It was striking that all of the experts pulled out general frameworks (i.e., prior theories) that organized large portions of their inquiry. I have labeled these domain frameworks, because unlike epistemic forms and games they are full of domain-specific content. For example, the notion of natural selection, with its ideas of random variation and survival of the fittest, might serve to organize how a scientist constructs a new theory of some process, such as idea propagation carried by memes. There was abundant use of analogies and metaphors in the protocols, and they appear to be functioning as domain frameworks. I will give four examples of domain frameworks organizing an inquiry, but there are many more contained in the protocols.

- *Law of Supply and Demand.* The three scientists all attacked the wages problem using the law of supply and demand to organize their search for factors that might cause a decline in wages. To do this they looked for things that might increase the supply of labor or decrease the demand for labor or for goods produced by the labor. Supply and demand is a complex idea with many facets, and it clearly played a large role in their inquiry. But it is a domain framework rather than an epistemic form.

- *Frontier Metaphor.* The historian in working on the resources problem invoked the parallel to the American frontier, as Frederick Jackson Turner proposed, where people would move on to new territories when the land or resources in a particular place were used up. She came to see resources as like the frontier and so organized her inquiry around the way that people would move on to other resources when the old ones were used up.
- *Light-bulb Metaphor.* The physicist spent a good deal of time elaborating how technology developments lead to decreased need for labor in terms of the development of the light bulb. He described how each individual element in a light bulb used to be made by hand and how there are now machines that turn out light bulbs very fast. This allowed him to develop a whole causal story that was part of the larger picture he developed in terms of the law of supply and demand.
- *Principle of Decreasing Costs of Natural Resources (Julian Simon model).* The psychologist in working on the resources problem invoked a hypothesis from Julian Simon, an economist, who argued that the cost of resources has followed a long-term trend of declining prices over time in real terms. The psychologist used this framework to predict how food, energy, and mineral resources would fare over the next 50 years.

Analysis of Three Protocols

In order to illustrate how these different elements came together in the protocols, I will describe three protocols: two generated by the psychologist on the climate and resources problems and one protocol generated by the physicist on the wages problem. These protocols illustrate the kinds of knowledge creation that were pervasive in the protocols.

Climate Problem. On the problem to predict the climate over the next 10,000 years, the psychologist started identifying key variables and their effects on climate trends. He talked about three variables (rejecting others as insignificant or unpredictable): (1) orbital variations (Milankovitch cycles), (2) pollutants or dust particles, and (3) greenhouse gases. From the readings he decided that orbital variation would be taking us toward another ice age, if it were not for the increase in greenhouse gases.

He spent a fair amount of time testing the hypothesis that greenhouse gases have a bigger effect on climate than orbital variation. He was concerned about the size of effects in order to determine whether the current warming will be overridden by a new ice age driven by orbital change. He decided that greenhouse gases had the larger effect. He then developed a two-stage model: he thought greenhouse gases would dominate in the first stage, leading to an exponential increase in temperature, followed by a second stage where man controlled the climate and reduced it to a desired level by controlling greenhouse gases and dust particles.

He made a distinction between three kinds of effects: (1) natural variation as in the Milankovitch cycles, (2) inadvertent side effects such as the production of greenhouse gases, and (3) main effects such as when humans try to counter greenhouse effects by releasing aerosol particles into the upper atmosphere.

When he came to plotting his predictions, he ended up with three phases in his stage model. The first was an exponential increasing function caused by the increase in greenhouse gases, partially offset by orbital variation and dust particles. The second phase was a decreasing function down to a level below current temperatures, caused by orbital variation as the world heads toward another ice age after people reduce emission of offsetting greenhouse gases. The third phase showed an increasing asymptotic function up to some optimal level near current temperatures, as humans learn to control temperature through greenhouse gas emissions and other mechanisms.

His predictions combined two of the epistemic forms: stage models and trend analysis. Such combinations of different epistemic forms are common in creating complex theories (Collins & Gentner, 1983; Frederiksen & White, 2002; Frederiksen, White, & Gutwill, 1999; Stevens & Collins, 1980). His stage model specified reasons for particular trends and reasons for a transition from one stage to another. His trend analyses built on knowledge about different processes and the kinds of functions they produce (e.g., what processes produce exponential vs. asymptotic functions).

The *domain framework* that he identified in his protocol was an additive model of the effects of different climate variables. In the model he assumed that a number of different variables have an effect on climate and that these combine in an additive way. The *epistemic strategies* involved identifying factors and determining their effects on the dependent variable. The *epistemic form* he developed was a hybrid stage model with embedded time-series analyses. The *key variables* he used were greenhouse gases, dust particles, and orbital variations. The *epistemic concepts* he concerned himself with were types of functions (e.g., exponential and asymptotic), size of effects as between different variables, lag effects from introducing greenhouse gases and dust particles into the atmosphere, side effects from using fossil fuels, and main effects from releasing aerosol particles to reduce warming.

Resources Problem. The resources problem asked subjects to make predictions about food, energy, materials, pollution, and wildlife over the next 50 years. The psychologist started his analysis based on one of the readings he was given. It led him to start with a domain framework that I will call the Lester Brown model of resource depletion (Brown, Flavin, & Kane, 1996). In this view, land for growing crops is being lost to soil erosion, salination, and other uses; natural resources are finite and are being used up; and we are reaching the point of diminishing ability to increase resource production to accommodate increasing population.

But after pursuing this framework for a short while, he switched to another framework I will call the Julian Simon model of infinite resources, based on one of the readings among the materials provided (Simon, 1995). He used the Simon model thereafter in making predictions about food, energy, and mineral resources. According to the Simon model, the cost of resources over the long run always decreases, because of substitution, improved production techniques, and opening up of new sources. The decreasing cost reflects increasing supply relative to demand (based on the supply and demand domain framework). Therefore, he predicted a decreasing demand for food, energy, and mineral resources over the next 50 years.

This model led him to treat the increase in grain prices in the 1990s as an anomaly to be explained. His explanation was that fertilizer had been heavily subsidized by the Soviet Union, so that when it collapsed and fertilizer was sold at world market prices, there was a large decrease in its use throughout Eastern Europe. He also considered the high oil price anomalies in the 1970s and 1980s caused by the oil cartel and Saudi Arabia's willingness to cut back on production. Because substitution and opening up of new sources are processes with lags, sudden changes in the situation can lead to temporary price increases. This kind of attempt to explain anomalies was also seen in the teenager protocol by the historian.

The psychologist took a different tack for species and pollution. For the species prediction he made a segmentation of the population into three groups, which he thought would have distinguishable fates. The first group included large animals people care about, which he thought would be saved in captivity, even though their natural habitats were being wiped out. The second group included insects and other animals that can thrive in conjunction with human habitation. The third group, which he treated as the norm, included all the animals that he felt would be wiped out as humans change more of the ecosystems of the planet. In this analysis the last group reflected his general extinction framework, while he treated the other two groups as anomalies from the normal pattern.

He also made a two-part segmentation with respect to the pollution issue, into a prediction for the developed world and a prediction for the developing world. His domain framework was a historical view that pollution increases with population growth and industrialization up to the point that the society is wealthy enough to take measures to counteract it, at which point it starts decreasing. Different countries are at different points along this continuum, so that for developed countries he predicted that pollution would generally decrease, and for developing countries it would increase to a point and decrease subsequently. Running through these predictions was a distinction between natural processes, the side effects of human activities, and human countermeasures or control processes. These were the same kinds of processes he discussed in the climate question.

There were five *domain frameworks* that emerged in the resources problem: (1) the Lester Brown model of resource depletion, which was abandoned, (2) the Julian Simon model of infinite resources, which was applied to the food, energy, and mineral resources predictions, (3) the habitat destruction model of species extinction, (4) the industrial and population growth model of pollution production, and (5) the human countermeasures model that he applied to both species extinction and pollution. His *epistemic strategies* involved identifying key variables, making segmentations, and explaining anomalies. The *epistemic forms* included a stage model, time-series analyses using different standard functions, and an implicit system-dynamics model derived from Julian Simon. The *key variables* he used were resource substitution, improved production techniques, new sources of resources, habitat destruction, population growth, industrial pollution, etc. The *epistemic concepts* he talked about were types of functions, side effects, and lag effects.

Wages Problem. The wages problem asked subjects to explain why wages in America had fallen from the early 1970s to the mid 1990s and to propose actions that could be taken to reverse the situation. The physicist spent the greater part of the protocol working from his supply and demand model trying to identify all the possible variables that might cause wages to decline. When he would identify a possible variable, he would then try to construct a causal chain to see if it would lead to a decline in wages, given his supply and demand model. Hence during most of the protocol he was applying a hypothesis formation and testing strategy to construct his theory.

He started off focusing on the key variable of productivity, which he defined in his notes with the equation: Productivity equals the value (of goods and services) produced divided by the labor cost to produce it. The major variable that he thought would affect productivity was technology. It was in this context that he brought out his light-bulb metaphor, describing how when Edison first invented the light bulb, workers had to make each element by hand, while now machines turn out many light bulbs each hour with very little labor input. His reasoning was that as we develop better technology and techniques, we need less labor to produce the same amount of goods. As the demand for labor goes down, wages also decline, since there will be more people competing for the same jobs. He further argued that increases in manufacturing productivity had driven people from manufacturing to service jobs, most of which pay lower wages.

Then he looked at a book on demography (Easterlin, 1980) and started thinking about the baby boom entering the work force during the period. He questioned whether this would lead to lower wages, since the increase in workers would be offset by the increase in consumers (i.e., the increase in labor supply could be offset by an increase in the demand for goods). But he decided in the end that having a large number of young people coming into the work force would lower wages, because entry level jobs pay much lower wages.

Concerns with demography led him to think about the surge of women into the work force during the period, which would increase labor supply and drive down wages. This led him to construct a two-state model, in which America moved from state 1 with high wages, women not working, and a family income about the same as in the subsequent state 2 with lower wages and women working. Demography also led him to consider the flood of immigrants in recent years that could drive down wages. The concern about immigration led him to consider the "institutional setting" where different government policies, such as immigration laws, collective bargaining rules, and minimum wage laws, might affect wages. In passing he worried about the side effects of raising the minimum wage too much, which could lead to decreased employment. He did not construct a causal chain from most of these institutional variables to lower wages, though he did discuss how the decrease in unionization might have led to lower wages.

In considering a book comparing wage rates in different countries (Freeman, 1994) he focused on the large relative disparity of wages in America between the top 20% and the bottom 20%. This led him to focus on the difference between the average wage and the median wage. He thought that the average wage might go up as the wage disparity increases, while the median wage goes down. So he thought that the increasing wage disparity in America might be contributing to a decline in median wages, as the rich get a greater share of the wages.

As he worked on the problem, he made a three-way segmentation into the different kinds of variables that affect wages between (1) the changing demographic factors, such as the baby boom and women entering the workforce, (2) the changing institutional settings, such as labor unions and minimum wage laws, and (3) the changing global context, such as new technologies and moving jobs offshore. That was how he framed his final theory.

When he turned to the question of how to counteract the decline in wages, he did not spend much time attempting to counter the weak links in his explanation of falling wages, though he did suggest you could raise the minimum wage and change laws to strengthen labor unions. Instead, he focused on how you could improve education levels of the population, thereby increasing people's ability to compete in a global marketplace.

In summary, the *domain frameworks* he employed in his analysis centered on supply and demand, with reference to other domain frameworks such as the global market, the institutional context in America, demographic forces, and the light-bulb metaphor for technological change. The *epistemic forms* he employed were causal chains, a two-stage model of women's entry into the workforce, and a multi-factor model of the overall causal factors that led to a wage decline. The *key variables* he focused on included productivity, technology, labor supply and demand, and a variety of demographic variables, institutional variables, and global market variables. The *epistemic concepts* he mentioned were side effects and the difference between the average and the median. The *epistemic strategies* he employed included forming and testing hypotheses, determining the effect of one variable on another, segmentation into different types of factors, and countering weak links.

Discussion

I think the five epistemic elements (i.e., epistemic forms, epistemic strategies, key variables, epistemic concepts, and domain frameworks) identified in the protocols are the epistemic tools researchers use to create their theories. They are powerful tools for making sense of the world. To the degree a person is equipped with a large set of these tools, they are empowered to understand what is going on in the world around them.

Below I discuss each of these five elements, as well as their importance for science education and making sense of phenomena in the world.

Epistemic Forms. Some of the epistemic forms we described in our earlier papers (Collins & Ferguson, 1993; Morrison & Collins, 1995) did show up in the protocols.

In particular the experts constructed stage models, time-series analyses, comparison tables, causal chains, multi-factor models, and a system-dynamics model. There was one new form, a finite-state model, which the physicist constructed for the wages problem. The epistemic forms used were all static forms which, given the nature of their working situation, were inevitable. However, the biologist's system-dynamics model could have been entered into a computer to become a dynamic model. The protocols did not reveal anything specific about the epistemic games the subjects used to fill out the epistemic forms they employed.

Epistemic Strategies. The epistemic strategies used by the experts are general-purpose strategies for constructing theories, such as the hypothesis formation and testing and the segmentation seen in the psychologist's and physicist's protocols. I first encountered this kind of epistemic strategy in a middle school science class where the teachers employed what I labeled the "theory-and-evidence game" in order to get their students to carry out scientific inquiries in the context of measuring shadows and trying to understand the dynamics of the relationship between the earth and sun. The goal was not simply to teach students to distinguish between theory and evidence, or observation and inference, as occurs in some school classrooms. Rather the goal was to teach students how to make sense of phenomena by reasoning about theory and evidence in many of the ways that scientists do.

The theory-and-evidence game goes in two directions: from evidence to theory and from theory to evidence. The goal in going from evidence to theory is to construct a theory that can account for observations or data that have been collected. The theory construction part of the game was the focus of the classes that I analyzed in detail. Some of the moves the teachers applied to theory construction are shown in Table 2.2. The overall goal of their theory construction, represented by 1.0, was to find patterns in data and construct an explanation to account for those patterns. Where data did not fit the patterns, then the goal was to find the reason why the anomalous data did not fit the pattern of the other data. Two strategies for explaining anomalous data are elaborated in 1.1, which in turn are elaborated further in 1.2 and 1.3.

Some of the epistemic strategies used by the experts in the protocols appear to be subparts of this theory-and-evidence game. In particular the hypothesis-and-testing strategy and the looking-for-anomalies strategy are closely related to the theory-and-evidence game as described in Table 2.2. It is certainly possible that a more complete description of the theory-and-evidence game would incorporate all of the epistemic strategies the experts were using. The theory-and-evidence game as taught by the two teachers I studied seems like a powerful way to learn important aspects of the way experts construct theories.

Key Variables. It was striking how the three scientists organized much of their work around identifying key variables related to the questions, and trying to link them into causal chains or other configurations, such as multi-factor models or a system-dynamics model in one case. This suggests that the idea of a "variable" is a key idea for scientists in making sense of the world. Some of the variables considered by the scientists, such as the number of women entering the work force

Table 2.2 Theory construction moves in the theory-and-evidence game

1.0 Construct a new theory
1. Identify patterns in any data collected
2. Compare data from different situations to identify generalizable patterns
3. Construct a theoretical explanation for the patterns identified
4. Explain any anomalous data that do not fit the theory
1.1 Explain anomalous data that do not fit a theory
1. Attribute the anomaly to variability in the data
2. Attribute the anomaly to an error in measurement
1.2 Correct for variability in data
1. Identify constructs that might cause the variability in the data
2. Redo the experiment while controlling the constructs identified
1.3 Correct for error in measuring or calculating
1. Have different experimenters measure the data independently and take consensus
2. Have a team of people carry out the measurements carefully
1.4 Make predictions from a theory
1. Identify cases for which no data have been collected
2. Extrapolate from the theory to specify what the data should be for these cases
1.5 Test predictions from a theory
1. Set up experiment to test the cases for which predictions have been made
2. Collect the data for these cases and compare to the predictions

and orbital variations are very complex variables. How well most people understand this complex idea of a "variable" is an open question, nor is it clear that how well the idea is taught in schools. The idea of a "variable" is mostly taught in algebra classes, where it is abstracted from the kinds of uses the scientists were making of it in their protocols. So it may be that most people have been exposed to the idea of a variable in school, but have little understanding of its use in making sense of the world.

Epistemic Concepts. The three scientists worried about concepts like lag effects, side effects, types of functions, the difference between the median and average, and feedback loops in constructing their theories. These are domain-independent concepts that are critical in much of scientific thinking. There may be a large number of such concepts, though I only identified a few in the protocols. They are clearly powerful ideas, like the idea of a "variable." In fact the idea of a "variable" could be considered one of this class of epistemic concepts. It would be good to identify a more complete set of these epistemic concepts, but it is beyond the scope of this chapter to do so. It clearly is critical for students to learn about these epistemic concepts in order to think more productively.

Domain Frameworks. The most surprising finding to me from the study was the role that domain frameworks played in the way these researchers constructed their theories to address the difficult questions posed to them. Domain frameworks organized their search for information to construct their theories. In fact the theories constructed can be thought of as instantiations of the domain frameworks with respect to the specific problem they were asked to address.

The domain frameworks used by the experts ranged in quality from concepts central to particular domains such as supply and demand in economics, to hypotheses such as the Julian Simon and Lester Brown models of resource consumption, and to metaphors such as the physicist's light-bulb metaphor and the historian's frontier metaphor derived from Frederick Jackson Turner's writings.

These domain frameworks are clearly essential epistemic tools for making sense of the world. They are the kind of powerful ideas that Papert (1980) described in his book *Mindstorms*. They are generative in the sense that they give people the power to make sense of new problems and phenomena, as we see in the protocols. They are the kind of domain content that education needs to focus on.

Societies need to teach people to use all these epistemic tools, in order to produce flexible thinkers to do the kinds of intellectual work that is needed to succeed in a complex world. This requires a rethinking of what is important to teach students around the world.

Conclusion

These findings have profound implications for science education. The five kinds of epistemic tools identified in the protocols are important for learners to acquire as they go through school, particularly if they aspire to become scientists. But even for non-scientists, these are useful tools for thinking about how to solve problems and make sense of the world. These epistemic tools have very wide applicability, which makes them powerful ideas in Papert's (1980) terms. This study only identified a few of these powerful ideas, so it is important that future research identify the important domain frameworks, variables, epistemic strategies, concepts, and forms that are critical to different sciences.

If these epistemic tools are going to be taught in schools, they are best taught by having students trying to construct models to account for different phenomena. Simply naming the different kinds of tools and having students use them in exercises, like much of schooling, is not likely to lead to a lasting effect. Rather teaching should reflect the kind of approach that the two teachers who guided their students through the theory-and-evidence game used with their middle schools students. They set a general problem about the length of shadows, sent the students out to collect data, and asked them to construct a theory about the relation of the length of shadows to objects. This is basically a cognitive apprenticeship approach to teaching scientific reasoning (Collins, Brown, & Newman, 1989). Given a variety of problems to solve and theories to construct, students will learn to use the kinds of epistemic tools that these experts were using. As students encounter these different epistemic tools in their work, teachers need to emphasize their power and generalizability.

A major point I want to make from this analysis of protocol data is that it is possible to study systematically how experts construct their theories. While this method only touches the beginnings of the process of theory construction, it should be possible to probe even more deeply into the process with more extended analysis. The study revealed many aspects of the process of theory formation. It turned out that while epistemic forms and games were clearly important aspects of the process, equally important were the domain frameworks in organizing the theory construction process. There were also a number of general-purpose epistemic strategies and epistemic concepts that guided the inquiry process. And central to all the inquiries were the attempts to identify the key variables or factors around which to build a theory.

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Chapter 3
The Nature of Scientific Meta-Knowledge

Barbara Y. White, Allan Collins, and John R. Frederiksen

Introduction

We argue that science education should focus on enabling students to develop meta-knowledge about science so that students come to understand how different aspects of the scientific enterprise work together to create and test scientific theories. Furthermore, we advocate that teaching such meta-knowledge should begin in early elementary school and continue through college and graduate school and that it should be taught for all types of science, including the biological, physical, and social sciences.

In this chapter we outline a theory of scientific meta-knowledge, which is built around four critical aspects of science. We refer to the four types of meta-knowledge that are needed as (1) meta-theoretic knowledge, (2) meta-questioning knowledge, (3) meta-investigation knowledge, and (4) meta-analytic knowledge. While numerous investigators, working in the philosophy of science, cognitive science, and science education, have developed theories about various aspects of the nature of science, there have been few attempts to provide detailed models that explicate all four of these components, along with an elaboration of how they work together in scientific inquiry. This has resulted in science curricula that provide students and teachers with impoverished views of the nature of science.

Most K-12 inquiry-oriented science curricula, for example, underemphasize the role of theory, particularly competing theories. They also fail to adequately explain the relationship between theory and evidence, nor do they adequately portray the inquiry processes that are involved in the interplay between the two. Even college-level textbooks on research methods fall short. Most focus on investigation and analysis and do not adequately discuss the different forms that scientific models and theories can take or the types of evidence and arguments that can be used to support or refute them.

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_3,

This chapter is our attempt to provide a more comprehensive and integrated overview of what science curricula should aspire to teach about the nature and processes of scientific inquiry and modeling. Our Inquiry Island and Web of Inquiry learning environments and science curricula, which engage young students in theory-based empirical research projects, provide first steps toward putting this vision into practice.

Perspectives on the Nature of Science

The layperson's view treats science as made up of facts and theories that systematic observation and experimentation have established over time. This is a somewhat static perspective, which leads science education to emphasize the coverage of important scientific facts, concepts, and theories. In contrast, the predominant view among researchers in science education is that understanding the nature of science is important and that scientific inquiry and investigation are at the heart of the enterprise (AAAS; 1990; National Research Council, 1996, 2007). Those who hold this view have developed inquiry curricula that teach students how to form and test hypotheses, carry out careful observations and measurements, analyze the data they collect in their investigations, and report on their findings (see Anderson, 2002).

Some leading researchers in science education have emphasized the importance of argumentation between competing theories as the core activity of science (e.g., Driver, Newton, & Osborne, 2000; Duschl & Osborne, 2002; Duschl, 2007; Kuhn, 1993; Osborne, 2005; Smith, Maclin, Houghton, & Hennessey, 2000). They therefore design curricula that engage students in considering competing theories and in understanding how evidence can be developed to support or refute those theories (e.g., Bell & Linn, 2000; Sandoval & Reiser, 2004; Suthers & Weiner, 1995).

In another vein, some view modeling and theory construction as the central goals of science, where theories are coherent bodies of concepts, laws, and models, which account for a wide range of observations and enable humans to predict, control, and explain what happens as events occur (e.g., Collins & Ferguson, 1993; Gilbert, 1991; Halloun, 2004; Hestenes, 1987; Mellar, Bliss, Boohan, Ogborn, & Tompsett, 1994; Perkins & Grotzer, 2005; Slotta & Chi, 2006; White, 1993; Windschitl, Thompson, & Braaten, 2008). This view leads to science curricula that help students learn about the nature of scientific models and the process of constructing and testing theoretical models (e.g., Grotzer, 2003; Lehrer & Schauble, 2000, 2005; Schwarz & White, 2005; Smith, Snir, & Grosslight, 1992; Stewart, Cartier, & Passmore, 2005; White & Frederiksen, 1998).

Other researchers have emphasized the collaborative nature of science (e.g., Dunbar, 1999, 2000). Indeed, the scientific enterprise can be viewed as a form of collaborative learning that enables society to develop and test theories about the world. This perspective leads to instructional approaches that employ a "community of learners" approach (Bielaczyc & Collins, 2000; Brown & Campione, 1996), which emphasizes collaborative inquiry and knowledge building, to develop students' understanding of the scientific enterprise (e.g., Borge, 2007; Herrenkohl, Palinscar, Dewater, & Kawasaki, 1999; Hogan, 1999; Metz, 2000; Scardamalia & Bereiter, 1994).

We argue that all of these perspectives capture essential components of the scientific enterprise. Scientific inquiry can be viewed as a process of oscillating between theory and evidence, in a practice of competitive argumentation that leads teams of researchers to develop and test alternative scientific models and theories. The ultimate goal is to create theories and develop arguments, which employ explanations and evidence to support or refute those theories, and thereby convince other researchers of the merits of your team's "current best theory" (cf., Carey & Smith, 1993; Driver, Leach, Millar, & Scott, 1996; Duschl & Osborne, 2002; Duschl, 2007; Giere, 1992; Hammer, Russ, Mileska, & Scherr, 2008; Klahr & Simon, 1999; Krathwohl, 1998; Kuhn, Black, Keselman, & Kaplan, 2000; National Research Council, 1996, 2007).

The transition from making theories to seeking evidence, through an investigation, is one where the generation of questions and hypotheses derived from theory is crucial. The transition from carrying out an investigation to the refinement of a theory is one in which data analyses and syntheses are central. This view leads to a basic model of scientific inquiry that has four primary processes: (1) theorizing, (2) questioning and hypothesizing, (3) investigating, and (4) analyzing and synthesizing. Associated with each of these primary processes is a regulatory process that monitors how well the process is being carried out and whether another process should be invoked to deal with issues that arise (such regulatory processes, though important, are beyond the scope of this chapter and are addressed in White, Frederiksen, & Collins 2009).

In our earlier work on teaching scientific inquiry to young learners (White & Frederiksen, 1998), we portrayed such a model as an inquiry cycle, which provides a scaffold for inquiry in the form of a series of steps that one undertakes in a never-ending cyclical process of generating, testing, and elaborating scientific principles and models, with the ultimate goal of developing a widely useful, accurate, and comprehensive theory for a given domain. This is, of course, a simplified view: Mature scientific inquiry does not necessarily proceed in this stepwise fashion. For one thing, it is possible to start anywhere in the sequence. So, for example, one might start with vague questions that are not based on a particular theory or one might start with an investigation or with existing data to generate theoretical ideas. Furthermore, one does not necessarily proceed through these "steps" in order. For instance, analyzing data can lead to the need to do further investigation. So the critical components in the scientific enterprise are closely intertwined, and any view of science education that underplays one of these components fundamentally misleads students as to the nature of science (Chinn & Malhotra, 2002). Nonetheless, for pedagogical purposes, presenting students with an inquiry cycle, in which one starts with theorizing and questioning, is an effective initial model that can enable students to develop capabilities for inquiry, as well as an understanding of its constituent processes (Frederiksen, White, Li, Herrenkohl, & Shimoda, 2008; White & Frederiksen, 1998, 2005).

This model of scientific inquiry reflects the way most sciences include two camps: the theoreticians and the empiricists. Theory and empirical investigation form the two poles of science. Research questions form a bridge between these two poles, in which competing theories generate alternative hypotheses about the answer to a question, which then are tested through empirical investigation. Analysis and synthesis form the other bridge between the poles by providing ways to represent and interpret data from the investigation to bear on the theories in competition and synthesize a new "current best theory."

Scientific knowledge in a field such as physics is usually thought to include basic theories (e.g., Newton's Laws) and concepts (e.g., acceleration), as well as problem solving, investigation, and data analysis methods. We argue that there is meta-knowledge sitting above this basic scientific knowledge that characterizes the different kinds of models, research questions, investigation methods, and data analysis techniques and the relations between these different aspects of science. This kind of meta-knowledge provides scientists with a toolkit of representations and techniques that enables them to be more productive thinkers and better researchers. We think that making scientific meta-knowledge explicit should lead to improving science education, as well as to improving the methods and practices of science.

The inquiry cycle underlying our analysis of scientific meta-knowledge is in fact embedded in the standard form of empirical articles: i.e., introduction, methods, results, and discussion. The introduction relates the investigation to existing theory and derives the research questions and hypotheses that the investigation addresses. The methods section describes how the investigation was carried out. The results section describes the data analyses and the findings from those analyses. The discussion section then brings the analyses back to existing theory and how it should be modified based on the findings. Hence the inquiry cycle we utilize is deeply embedded in the culture of science.

Most scientists tend to focus their efforts in one area or another. For example, some scientists are strong in theory, some in designing investigations, and some in data analysis, while others are more balanced in their approach. It is not necessary that a given scientist be an expert in all aspects of scientific inquiry, but the field must encompass all these different components. We would argue, however, that science education should emphasize an understanding of all the components so that learners come to appreciate what is entailed in constructing theories, generating research questions and hypotheses, designing investigations, and analyzing and synthesizing interpretations of the data to generate arguments that support or refute particular theories. Such an overview is critical to understanding the nature of science (Lederman, 2007).

We became sensitive to different kinds of scientific meta-knowledge in developing advisory systems, Inquiry Island and the Web of Inquiry, which guide students as they do science projects that require them to engage in theory-based empirical research (Eslinger, White, Frederiksen, & Brobst, 2008; Shimoda, White, & Frederiksen, 2002; White & Frederiksen, 2005; White et al., 2003; White, Shimoda, & Frederiksen, 1999). These systems incorporate much of the scientific meta-knowledge we outline below in their various advisors. They include

Quentin Questioner, Hugo Hypothesizer, Ivy Investigator, AnnLi Analyzer, Sydney Synthesizer, and Morton Modeler. These advisors, who live on Inquiry Island, offer guidance to students when they seek help or encounter problems. Each advisor presents goals, purposes, plans, and strategies, as well as definitions and examples, with respect to their particular component of the scientific inquiry process. We think of Inquiry Island as one way to make different facets of scientific meta-knowledge available to students and teachers.

In order to illustrate our views about scientific meta-knowledge, we will use examples from the domain of social psychology. Working with Inquiry Island and the Web of Inquiry, we have begun to develop different models of friendship that students can manipulate and refine. Our goal is to make scientific models readily accessible and modifiable by students so that they begin to develop an appreciation of the power of models for understanding and refining theories. Rather than providing students with models that reflect the "received truth of science," such as Newton's laws, we want to provide students with models, such as models of friendship, which they can critique. The students then are able to test and refine the models or reject them altogether and create new models that reflect their understanding of friendship. In this way students are acting like scientists, searching for weaknesses in models, running models under different conditions, and engaging in empirical research in order to test and refine the models. They are learning how theory development and refinement generate empirical questions and investigations. We will use these friendship models and possible investigations to illustrate the different kinds of scientific meta-knowledge that we think are important.

In the next four sections, we describe meta-scientific knowledge in terms of its four components: meta-theoretic knowledge, meta-questioning knowledge, meta-investigation knowledge, and meta-analysis knowledge (note that we do not mean "meta-analysis" in the statistical sense). We should emphasize though that meta-questioning knowledge includes meta-knowledge about forming both research questions and hypotheses, while meta-analysis knowledge includes meta-knowledge about data analysis and synthesis. For each of the four sections, describing the four types of scientific meta-knowledge, there are five subsections that explicate the different aspects of the meta-knowledge: (1) the different types, (2) the purposes, (3) the creation process, (4) the criteria for evaluation, and (5) the synthesis of the different types. In a final discussion section, we summarize the framework and discuss the issues it raises.

Meta-theoretic Knowledge

Different Types of Models

Meta-theoretic knowledge includes knowledge about the nature of scientific models and theories. In our work on epistemic forms and games (Collins & Ferguson, 1993), we characterized three types of theoretical models (or epistemic forms) that researchers use to guide their inquiry: structural, causal (or functional), and dynamic process (or mechanistic) models. The different forms of structural models include primitive elements (e.g., chemical elements), stage models, cross product tables (e.g., the periodic table), hierarchies, and comparison tables. Similarly there are different types of causal models, such as causal chains, form–function analysis (e.g., Hmelo-Silver & Pfeffer, 2004), and multifactor models (as in medicine). Grotzer and Perkins (Grotzer, 2003; Perkins & Grotzer, 2005) present a more detailed taxonomy of causal model types. Finally there are different process model types, such as system-dynamics models (e.g., Mandinach & Cline, 1994), production systems (Newell & Simon, 1972), and agent models (e.g., Wilensky & Resnick, 1999). All of these representational forms have epistemic games (i.e., rules and strategies) associated with them, which are practices scientists use as they construct models to characterize and theorize about different phenomena.

We can illustrate the different model types with examples of friendship models for each of the three types: a stage model of friendship (structural), a multifactor model of friendship (causal), and an agent model of friendship (dynamic process). We want to reiterate that these models are not meant to be correct models, but rather models with enough intuitive grounding for young students to test and refine.

The stage model of friendship shows how the five top-level factors in the multifactor model of friendship (shown in Table 3.1) might change over time among pairs of friends. There might be variations on this stage model that reflect a friendship that lasts a very long time (delete stages 4 and 5) or a friendship that breaks up suddenly over some event (delete stage 3).

The multifactor model of friendship, shown in Fig. 3.1, postulates a possible set of factors that affect the strength of friendship between pairs of people. This model has five top-level factors (the same as in the stage model) and a set of factors that contribute to each of the five top-level factors.

We have developed some preliminary prototypes for a number of different agent models, where different types of people interact by calling one another on the phone. The information they communicate to each other (e.g., "so-and-so lied about you") leads the recipients to alter the values of parameters that reflect their feelings for each of the other people in the network, based on rules of the model (e.g., "if I

Table 3.1 A stage model of friendship that characterizes the relationship between two people

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
	Getting to know	Close friends	Drifting apart	Just broken up	Not friends
Trust	Increasing	Very high	Decreasing	None	Low
Common interests	Increasing	Many	Decreasing	Rejecting	Not applicable
Proximity	Seek out	Seek out	Seek sometimes	Avoid	Neither
Effort	Very high	High	Decreasing	None	Low
Communication	Difficult	Easy	Difficult	None	Easy

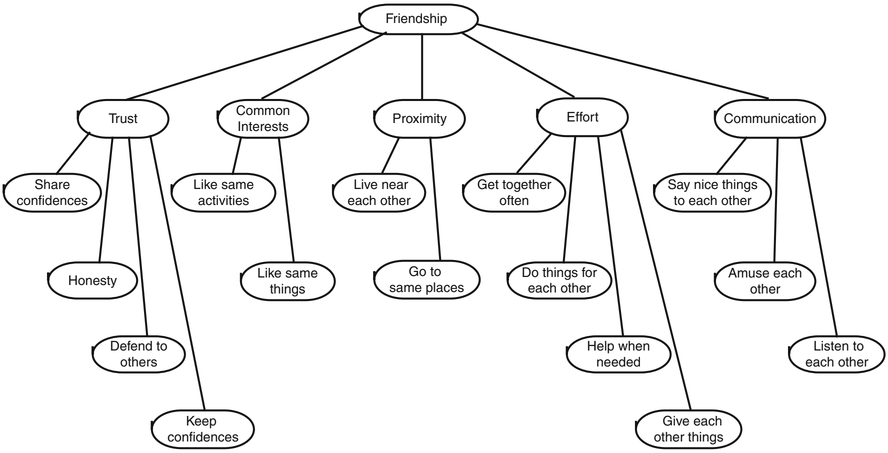

Fig. 3.1 A multifactor model of friendship

learn a person has lied about me, I will decrease my liking of that person"). These are simple agent models and lack graphic representations of the behavior of the agents, such as those in models like the Sims. However, they are both runnable and modifiable, so young students can see how the models behave under different input conditions and rules, which they then can modify. We will give a brief description of one of the more complex agent models.

An Agent Model of Social Interaction (Community Model)

This model embodies a personality for each person in a community, where the personality is determined by values on six different personality characteristics. People vary as to how appealing, amusing, talkative, honest, sweet, and shrewd they are. In this world, people call up people they like and tell them facts about people in the community and hear facts from the people they call. A person does not call the same person a second time until they have new facts to communicate.

People each start with 10 facts, assigned randomly, and acquire new facts that are generated throughout. They also remember any facts they are told. Each fact is about a person in the world and varies in truth and amusement value. People do not know about the truth of a fact, unless it applies to them or they made it up. Facts are remembered for a long time so that when new members join the community, the old members have lots of facts to tell them.

People tend to like people who are appealing and tell them amusing facts. Talkative people share more confidences and call more people. Dishonest people make up facts, and sweet people only say nice things. Shrewd people tell you nice things about people you like and bad things about people you do not like.

Each person has a degree of liking for each of the other people, which varies widely. Liking depends on many things, such as how appealing and amusing the other person is and whether you have discovered them to be dishonest. Depending on how much they like the person they are talking to, they will end the conversation sooner or later. Either party can end the conversation. The system can track how much each person likes the others over time to see how relationships in the community change over time.

Purposes of Different Models

Different model types serve different purposes. Structural models highlight the relationships between different elements in the models. Causal models depict the causal and functional dependencies between elements in the models. Dynamic process models allow one to run models of processes to see the consequences of different assumptions in the models. These runnable models can unpack mechanisms that explain the causal relationships depicted in static causal models, like the multifactor causal model shown above. Each different type depicts different relationships and properties. We will exemplify the purposes of different model types in terms of the three examples introduced above.

Stage models are valuable because they show how processes evolve over time. They are common in historical analysis, psychological analysis, and analysis of any process that can be characterized by a series of states. One of the most famous stage models is the cultural progression from hunter–gatherer to agricultural to industrial societies. Stage models help people to understand changes that occur in the world. For example, the stage model of friendship we presented in Table 3.1 might help children understand the way others are behaving toward them and even the way they are behaving themselves.

Multifactor models are a common way to analyze causality in systems. They are particularly pervasive in psychology and medicine, but are common in many other disciplines where events are caused by multiple factors. In well-specified multifactor models, variables (called factors or independent variables) are linked together in a tree structure. The branches of the tree are AND-ed together if the factors are all necessary to produce the desired value on the dependent variable. They are OR-ed together if any of the factors are sufficient to produce the desired value of the dependent variable. Often the factors are neither necessary nor sufficient, as in the multifactor friendship model we showed, where we identified a number of factors that taken together tended to facilitate friendship between pairs of people. Multifactor models are useful because they specify the different factors that produce a particular outcome and show how they are interrelated.

Agent models vary in the degree of intentionality the agents embody (Russell & Norvig, 1995). The friendship model we described has agents that have character traits, but no specific intentions. Other agent models we have been developing have different strategies for pursuing goals, such as getting people to like them. By running agent models, it is possible to see the consequences of different initial conditions and rules in the model. Some of the kinds of research questions that one might investigate with the model we described are the following: Do dishonest people start out being liked and end up being disliked? Are people with a few friends liked more intensely than people with a lot of friends? What happens when you introduce a liar into a community of honest people? Do people tend to make friends with people who have the same level of appeal? The power of agent models derives from the ability to study these kinds of questions and manipulate different rules and conditions to see the effects.

Creating Models

The different epistemic forms or model types are tools for making sense of the world. The structural forms are often the first forms people use to try to create a model. The simplest structural form is just a list so that if you are trying to account for the variables that affect friendship, you might start by creating a list of the causes or important factors that lead to a good friendship. As we explained in Collins and Ferguson (1993), a good list must satisfy a number of constraints: it should have multiple elements but not too many, the elements should all be of similar types, the elements should cover all the possibilities, and they should be mutually exclusive. If the list gets too long, or the elements are not all of the same type, then it might be that the list should be turned into a hierarchy or table, or one of the causal models, such as a multifactor model (see below). Trying to satisfy all these constraints helps the sense maker create the list.

Stage models are a simple type of time-structured list, but they invoke additional constraints. The simplest stage model is a list constructed with the constraint that the stages follow each other sequentially without overlap. Figure 3.2 shows a more complicated version of a stage model. Each stage might be characterized by multiple characteristics, and furthermore these characteristics may be arranged on a set of dimensions (e.g., the boy was angry and tired before his nap, but happy and energetic afterward). In a more complicated stage model, which is both structural and causal,

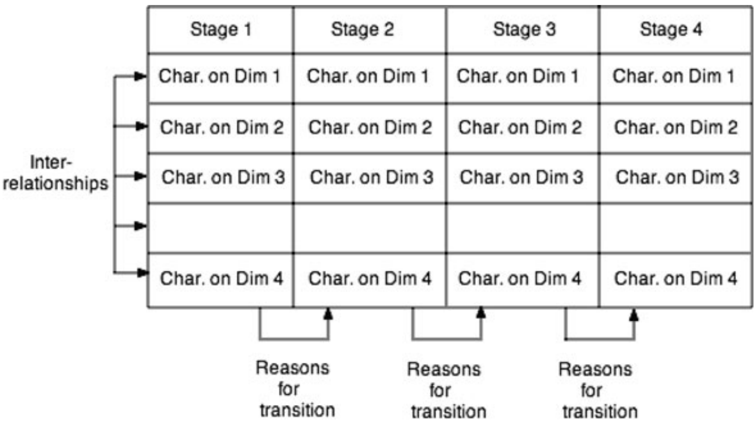

Fig. 3.2 A characterization of stage models

the interrelationship between the variables might be specified (e.g., energy state determines mood) and the reason for the change from one stage to the next specified (e.g., a nap leads to an increase in energy state). The last four constraints (i.e., multiple characteristics, specified dimensions, specified interrelationships, and reasons for transition) are all optional constraints that a person might or might not use in constructing a stage model.

We created the stage model of friendship shown earlier by first identifying a top-level list of factors (i.e., trust, common interests, proximity, effort, and communication) and treating these as dimensions that vary over time. Then we decided on a set of stages that friendships often follow and assigned values to each dimension for each of the stages we identified. As we mentioned earlier, one could also have a stage model for lasting friendships, or friendships that dissolve because of some incident, such as a deep disagreement, a betrayal of trust, or competition for another person.

Multifactor models are also created by starting with a list of factors that are conjectured to affect a dependent variable. Then the goal is to create causal chains that link the different factors to the dependent variable. Multifactor models can be expanded into system-dynamics models by adding feedback loops between the different variables. In the simple multifactor model of friendship we created, the different factors were assumed to affect one of the five top-level factors, which in turn affected the dependent variable (i.e., the strength of friendship).

Creating agent models is more difficult. The modeler first has to identify all the different kinds of agents that will live in the community and the kind of background world in which the agents interact. Then each agent needs to be given a set of states they can have (such as holding beliefs), actions they can take (such as talking to other agents), and reactions they can have (such as changing their beliefs), which can be specified in the form of rules for interacting with other agents in the world. If the agents possess higher order intelligence, one can also specify things like goals to pursue (such as getting people to like them), strategies for achieving the goals (such as flattering people), and even intentions or purposes to motivate them (such as the pursuit of happiness) (see Russell & Norvig, 1995). An important aspect of such a simulation model is how the behavior of the agents will be represented to the user, whether in dialog, tables, movement of agents around the world, or graphs of some kind. Many simulations of agent models provide multiple displays, which the user can manipulate in order to study different aspects of the behavior of the system.

Characteristics of a Good Model

There are a number of characteristics that a well-designed model should have. We have tried to characterize them in a way that is general to all of the different types of models:

- *Accuracy*: The model should accurately reflect some aspect of the way a system behaves or is structured. No model completely characterizes any system, but it should be accurate within the scope of its boundary conditions.

- *Generality*: The model should account for as wide a variety of phenomena in the world as possible. The model should cover all the phenomena within its scope.
- *Parsimony*: The model should be as simple as possible, but no simpler (to paraphrase Einstein). Parsimony helps to make the model clear and transparent to users.
- *Useful*: The model should have potential application to understanding and predicting the behavior of the modeled systems. While many models are constructed without regard to their application, the best models turn out to have useful applications.
- *Coherence*: The model should fit with everything that is known about the domain. In particular, as explained in the next section, it should cohere with other models to form an integrated theory of the domain.

How Different Models Fit Together

Scientific theories, in our view, are made up of a number of linked models. In chemistry, for example, the primitive elements (hydrogen, helium, etc.) are arranged in a cross product table (i.e., the periodic table). There is an underlying atomic structural model of protons, neutrons, and electrons arranged in shells that accounts for the structure of the periodic table. There are also constraints that determine how different elements combine into molecules, based on their atomic structure. Hence the standard theory in chemistry is made up of different types of models linked together in systematic ways.

In our prior work (Frederiksen & White, 2002; Frederiksen, White, & Gutwill, 1999; White & Frederiksen, 1990), we illustrated how various models of electrical circuits can be linked together to create a comprehensive theory of circuit behavior. Models of different types can be used to embody different perspectives on the behavior of a system. For instance, functional models can be used to show the purpose of a circuit and how subsystems within the circuit interact to achieve that purpose. Constraint models can be used to portray circuit behavior at the macroscopic level. They can reason about circuit behavior through the application of a set of laws that govern the distribution of voltages and currents within the circuit. Process models can be used to represent the behavior of circuits at a more microscopic level. They can show, for instance, how electrical forces within a circuit cause mobile charged particles to be redistributed when, for example, a switch is closed.

Such models can be linked in different ways. They can be linked derivationally when the behavior of one model type is emergent from the behavior of another model type (Wilensky & Resnick, 1999). For example, Frederiksen and White (2002) describe how their macro-level model of circuit behavior (which employs circuit laws) can be derived from the local-flow model of electricity they present, and how the local-flow model can be derived from their particle model of electricity (the micro-level model).

In addition, models can be linked developmentally when there is a "progression of models" (White & Frederiksen, 1990) such that a higher order model is created from a lower order model by adding new rules or entities. For example, a simple local-flow model of circuit behavior allows people to solve problems about serial circuits, and an elaboration of the model allows people to solve problems about serial, parallel, and hybrid circuits. Such model progressions, which lead to theory development, can involve the addition, modification, differentiation, or generalization of model components or even the construction of new models. Model progressions can be used to represent the evolution of scientific theories, as well as representing possible paths to understanding a domain (i.e., from low-level to high-level understanding).

The models of friendship we have been developing are linked together in various ways. We mentioned how the top-level factors in the multifactor model form the dimensions of change in the stage model and how emergent properties of the agent model appear in macro models such as the multifactor model of friendship. We have also developed a number of other models that are linked to the models shown: a flow model of trust, a system-dynamics model of popularity that links different variables in feedback loops, and an aggregate model of clique formation that reflects emergent behavior of the agent model described earlier. In addition, we have been creating a variety of agent models, one of which has agents that form friendships based on common interests and one where the agents pursue friendships using strategies derived from the multifactor model of friendship. The goal is for young learners to see how models at different grain sizes and addressing different phenomena are linked together to form a theory of a domain and how such a theory can evolve as research progresses.

Given the growing importance of modeling in science, we think it is critical that students learn about the different forms that models can take and how different models can be linked together to form a coherent and powerful theory. Hence, the essential meta-theoretic knowledge that people need to learn is how theories and models are created, refined, and extended. Our work on epistemic forms and games (Collins & Ferguson, 1993) is a preliminary attempt to outline how models are created. The work on linking models (Frederiksen & White, 2002; White & Frederiksen, 1990) is an attempt to characterize how different models can be integrated to form the theory of a domain, which has implications for how models are refined and extended. We think these various pieces fit together to form the basis for the development of meta-theoretic knowledge in science.

Meta-questioning Knowledge

Different Types of Research Questions

In order to evaluate models and theories, it is necessary to turn elements of the theories into research questions that can be directly investigated. Sometimes research questions are quite vague (e.g., What are the precursors to heart disease?) and sometimes the questions are specific (e.g., Does taking a particular drug reduce one's cholesterol level?). The hypotheses in any study are the different possible answers to a research question, which can be based on alternative theoretical positions. For example, in the Framingham Heart Study, which tried to identify precursors to heart disease, researchers identified some 200 plus possible precursors to measure. They then followed the people in Framingham over time to see if they developed heart disease. These 200 plus variables were their alternative hypotheses as to what might lead to heart disease.

The different epistemic forms (i.e., types of models) generate different types of research questions. Table 3.2 gives examples of the types of questions that arise in constructing structural models, causal models, and process models. These are not an exhaustive set of questions needed to construct the different types of models, but they are some of the most common research questions that arise as scientists create models to express and develop their theoretical ideas.

Table 3.2 Types of research questions generated by different epistemic forms

Form	Examples of questions
Structural	What are all the different types of X?
	What are the characteristics of X?
	What stages does X go through as it evolves?
	What are the components of X and how are they related?
Causal	Does Y cause X?
	What effect does Y have on X?
	What causes X to happen?
	What are all the factors that affect X?
Process	What process produces X?
	What are good strategies for accomplishing X?
	What are the rules of interaction between X and Y?
	What mechanism enables X to be achieved?

If possible, it is always best to construct research questions that differentiate between alternative theories or models. Any of the questions shown in Table 3.2 can be turned into a question to differentiate between two models. For example, the first structural question can be transformed into "Are the different types of X from set Y or set Z?" The first causal question can be transformed into "Does Y or Z cause X?" The first process question can be transformed into "Is X produced by process Y or Z?" Research questions that differentiate between alternative models force researchers to generate alternative hypotheses as answers to their question.

We can illustrate how the different types of research questions are tied to particular models in terms of the three models of friendship described in the previous section. These examples do not exhaust the possible research questions one can ask about each of the friendship models, but they do give the flavor of the kinds of questions each model provokes.

- The stage model suggests the following questions: What are the critical stages through which friendships evolve? Are there different trajectories for different

kinds of friendships? What are the critical characteristics on which the stages differ? What causes the transition from one stage to another?
- The multifactor model suggests the following questions: What are all the factors that affect whether two people form a friendship? Which factors have the largest effect? How do the factors combine to affect the degree of friendship? What causal chains link each factor to the degree of friendship?
- The agent model suggests the following questions: What strategies do people follow to get others to like them? What is the process of clique formation and do cliques change over time? Which kind of statements have the most effect on increasing or decreasing one's liking for another person?

Another type of research question addresses the issue of generalization. When one conducts an investigation, it is carried out in a particular context and, in the social sciences, with particular participants. In order to generalize the results of the study, it is possible to generate research questions of the type "Do the findings hold in other contexts?" or "Do the findings hold with different types of participants?" Establishing the bounds on models and theories is an important part of the scientific enterprise, and so these kinds of generalization questions are pervasive in research.

Purposes for Research Questions

The fundamental reason for constructing research questions is to derive some implication from a model or theory that can be directly investigated. Hence, research questions perform the job of narrowing down or extracting from complex theories a particular issue that can be studied. For example, Einstein's general theory of relativity was a broad and complex theory, which was not easy to test. But specific and surprising implications of the theory could be tested. One implication is derived from the theory's prediction that light waves bend in a gravitational field. Hence, a light source at a great distance, such as a distant quasar, should appear in two different places in the sky, if located behind an object with a strong gravitational field. The research question this generates is "Can we identify a distant object that appears in more than one place in the sky?" This question then led to a specific investigation that could test one implication of a complex theory.

Ideally research questions help to differentiate between possible theories. Finding crucial questions that in fact distinguish between alternative theories is very difficult. And when a crucial question is investigated, the researchers whose theories are not supported by the data usually can come up with some explanation that still preserves their theory, albeit in a modified form. But even in investigations that do not compare alternative theories, researchers have to come up with questions and data that enable them to differentiate their explanations for their findings from obvious alternative explanations that other researchers might generate.

Very often the purpose of a research question is to solve some practical problem or help achieve some worthy goal in the world. Hence the question driving the Framingham Heart Study (i.e., What are the precursors for heart disease?) was a very important research question to investigate, since so many lives depended on the answers that were found. In fact the study identified factors (e.g., smoking, high cholesterol, and high blood pressure) that could be treated, and hence the findings of the study have led to the saving of millions of lives.

Criteria for Good Research Questions

There is an art to generating good research questions. We have identified a number of characteristics that make for a good research question. These represent criteria that researchers should use when they generate possible research questions to investigate and need to choose which question(s) to pursue.

- *Interesting.* A good question addresses an issue other people care about. It is particularly interesting if the model or theory generating the question predicts a surprising answer to the question.
- *Worthwhile.* A question that addresses a salient issue in the world, such as the precursors of heart disease, is clearly worth pursuing.
- *Distinguishing.* A question that leads to answers that would help distinguish between competing theories is an important research question.
- *Accumulative.* If a question builds on previous research, it helps researchers create a more comprehensive theory for the domain being studied.
- *Feasible.* A research question needs to suggest investigations that can clearly be carried out and give results that fairly answer the question.

Generating Research Questions

There are generally three sources of research questions: theory, data, and practical issues or problems in the world. We will elaborate on how each of these sources acts to generate research questions.

When constructing a new theory, there are many questions that arise. As we indicated earlier, each of the epistemic forms or model types gives rise to a number of different questions. Testing the implications of a model similarly leads to a particular set of questions depending on the form of the model. And as we suggested, when there are competing theories, questions that distinguish the theories are particularly worth pursuing. Finally there are questions that come out of the limitations of any theory, such as questions of generalization or of filling in holes in the theory. For example, when Mendeleyev first constructed the periodic table, there were a number of elements that the table predicted should occur in nature, but that had not yet been identified. Hence his theory led to the research question: "Can we find elements with the missing characteristics?" As these examples suggest, models and theories are a very rich source of research questions.

In addition to theory, data or findings from an investigation often lead to new research questions. This happens in two ways. Often, some data found in a study seem to contradict the predictions from a theory. This can lead to revising the theory, but it can also lead to questions about boundary conditions of the theory (i.e., its generalizability). In other cases, patterns of data may not contradict the theory, but may suggest that the theory is incomplete in some way. In most cases, anomalous data suggest revisions to the theory, which in turn lead to new research questions.

As we indicated in our discussion of the Framingham Heart Study, research questions often arise to achieve goals that derive from needs or observations of the world. The history of science is filled with stories of how the world has posed questions for researchers that have led to important investigations in science.

How Research Questions Fit Together

When one research question is answered, it often raises a set of related questions. One way this occurs is when a particular structural pattern is found, as when Mendeleyev discovered the periodic table, it raised the question of why the elements in a single column have similar properties. This question led eventually to the model of the atomic structure of atoms. Similarly, a causal model, such as a multi-factor model, raises questions about the mechanisms that lead each of the factors to have the given effects. These two examples show how answering one research question can lead researchers to generate related questions about underlying processes, structures, and mechanisms, which in turn leads to more comprehensive theories for any given domain.

In summary, the meta-questioning knowledge that we think students need to acquire includes learning about the different types of research questions that can be asked and how each type of question is related to particular epistemic forms. Students also need to develop an understanding of how questions can be created to distinguish between competing theories and how, in the process of creating a deeper, more coherent theory for a domain, one question leads to another.

Meta-investigation Knowledge

Different Types of Investigations

The third component of scientific meta-knowledge is an understanding of the different forms that scientific investigations can take. There are many different investigation methods, but they generally fall into two basic types: (1) exploratory inductive investigations (often referred to as scientific induction) and (2) confirmatory investigations (often referred to as the hypothetico-deductive method). Exploratory inductive investigations are employed when one has broad research questions and some general theoretical ideas, which suggest interesting data sources to study, but which are not specific enough to generate particular hypotheses. The goal is to obtain data that will constrain one's efforts to develop more detailed models and theories. Confirmatory methods are used when one has a well-developed model, or set of competing models, which allows one to develop a set of theory-based hypotheses to test. The goal is to test each of the hypotheses to see if the findings are consistent with its theoretical predictions. This allows one to determine which models are most consistent with the data and which are not suitable for explaining the phenomena that have been investigated.

Exploratory Inductive Investigations

Galileo is famous for developing exploratory inductive methods in science. In his experiments on pendulums and gravity, he systematically varied the elements that he thought might affect the period of the pendulum and the speed of a ball rolling down an incline. From these exploratory investigations, he derived equations for the motion of pendulums and falling bodies. The Framingham Heart Study is a modern variation on his method using natural variation rather than controlled manipulation. The investigators in this study collected data from many people in Framingham Massachusetts on a large number of variables that they thought might influence the likelihood of getting heart disease. They then followed the people over many years to see if they developed heart disease and identified a number of variables that were precursors to heart disease.

The kind of data collected in exploratory investigations has a strong effect on the types of models that can be constructed from the data. Quantitative data support the construction of constraint-equation models, as we see with Galileo, or multifactor models, as we see in the Framingham Heart Study. To construct process models, such as the agent model described earlier, one needs a richer data stream, such as observational, protocol, or discourse studies provide. The goal of exploratory studies is to identify patterns in the data and systematic relationships that allow for the construction of models. These models can then be evaluated using confirmatory methods.

Confirmatory Investigations

Confirmatory investigations, which are designed to test theory-based hypotheses, can take many different forms. The best known is the randomized controlled trial, in which one or more hypotheses are tested by comparing conditions that correspond to each of the hypotheses being tested. Often such a test of a hypothesis contrasts an "experimental" condition, which includes some particular feature, with a control condition that lacks that feature. In such cases, the competing hypothesis is that the feature will have no effect, which is known as the "null hypothesis." In order to ensure the generality of the findings, the participants, or objects being studied, are assigned randomly to the different conditions. Often special efforts are made to control any variables that might affect the results, other than those being deliberately varied. After the experiment has been carried out, the data are analyzed to see if they are consistent with what was predicted by any of the hypotheses.

In one example of such a randomized controlled trial, we tested hypotheses about the impact of self-assessment on students' learning (White & Frederiksen, 1998).

In this study, three middle school teachers taught science lessons in two different ways using our ThinkerTools Inquiry Curriculum in which students construct theories of force and motion. By randomly assigning their classes to the experimental or control conditions, it was possible to hold the teacher variable constant. The experimental group engaged in systematic self-assessment of their work, whereas the control group spent the same amount of time reflecting on what they liked and did not like about the ThinkerTools learning environment. The experimental group showed significant gains as compared to the control group on a number of different assessments of their learning. The findings support the theory that self-assessment can positively impact the learning of science and scientific inquiry. One advantage of collecting multiple measures of performance is that the patterns found can lead to further hypotheses and theory refinement, such as theories about the impact of low-achieving students working on self-assessment in collaboration with high-achieving students.

Examples of Investigations

We can illustrate different confirmatory and exploratory investigation methods in the context of creating and testing models of friendship. In order to construct a multifactor model of likeability, students could break into groups to conduct interviews or surveys of people they know in order to identify critical factors. They might ask: What is it about other people that makes you like them? If different groups of students construct different multifactor models of likeability, these models could be tested by different confirmatory methods.

One kind of confirmatory study might set up a series of small parties, where actors talk to different people, who do not know the nature of the study. The actors would apply different strategies to get people to like them. Each actor would apply a different strategy in each party so that the strategies and actors are properly counterbalanced. For example, one pair of actors could use a flattery strategy, another pair could appeal to common interests, and a third pair could tell amusing stories. After talking to each person, the people participating in the party could rate each of the actors on likeability. The average likeability rating for actors using each different strategy would be a measure of the strategy's effectiveness. This experiment thus could determine which of the strategies is most effective and the relative efficacy of each.

Another kind of study, using observation and interviews, might be helpful for constructing a stage model, a multifactor model, and an agent model of friendship. The idea is you would study how the relationships in a new group of people evolve over time—for example, a book group made up of people who do not know each other beforehand. The book group would be videotaped, and interviews would be conducted with each participant shortly after each meeting. The interviews might ask (1) How do you feel about X and why? (for X = each person), (2) Did you do anything to make others like you?, and (3) Did you do anything to attract or repel X and if so what? The research questions could be the following:

- How do the relationships change over time?
- What factors determine how much each person likes another?
- What strategies do people use to attract or repel others?
- Do cliques form and change over time? What is the process of clique formation?

Purposes of Different Investigations

The goal of exploratory investigations is to create or refine a model. Often different methods are applied to triangulate on the phenomena in order to construct a more robust model. Different inductive methods should be applied depending on the type of model the investigator is trying to create. We described one method that might be used to create a multifactor model, though such self-report data may be systematically biased. If one wanted to create the kind of agent model we outlined in the theory section, you would need to apply more intensive methods. For example, you might carry out an observational study in different groups, with cell phones that record all conversations, in order to identify salient personality types, the nature, duration, and frequency of the messages between different people, and the bases for the cliques that form among the groups. A limitation of such intensive investigations is that the researchers may have systematic biases in what data are collected and in how they are interpreted. That is why confirmatory studies are critical to the development and refinement of models.

Confirmatory investigations are needed to evaluate the accuracy of models and to resolve conflicts between different theories. They are also critical to determining the boundary conditions for different models in order to decide the range of situations to which the model applies. As described above, theories and models generate research questions, which in turn generate hypotheses. These hypotheses are then tested with investigations designed to see whether or not the prediction made by each hypothesis is supported.

Creating Investigations

There are a number of steps to creating an investigation. The first step is usually to decide on your research questions. Some research questions, such as "what are all the factors that affect X," lead to exploratory investigations. Other questions, such as "does X have a positive effect on Y," suggest confirmatory studies. In order to address your question, you need to simulate the situation or process you are trying to model. If your question is "what factors affect whether a person likes another person," you need to create a situation where people are deciding whether they like someone or commenting on why they like or dislike other people. If you want to know whether a particular strategy causes people to like the person employing the strategy, then you need to create a situation where people are judging other people who employ that strategy. If you have complex research questions, such as "How do cliques form in a community?" and "What are the characteristics that determine which people form cliques together?", then you need to carry out an investigation that embodies the entire process of clique formation.

Next you have to decide how to collect a representative sample with respect to the phenomena the model addresses. If you are surveying or interviewing people, you choose a random sample of people who fit the class that the model is supposed to characterize. If you are creating a situation that is supposed to reflect situations in the world, then consider whether there are characteristics of the situation you have created that will bias the results you find. For example, if you are creating a party where actors are trying to make people like them, it is important to select a random sample of people that is large enough to represent the population you are modeling (e.g., high school students). It is also critical to consider ways that the party might be unrepresentative of the ways that people form opinions about others. Ensuring that the subjects are unaware of the nature of the experiment is one way to make the party more representative, but it is still a highly artificial situation that distorts in different ways the basis on which people form opinions about others. To compensate for this artificiality, it is necessary to carry out other investigations that address the same issues.

To carry out an investigation, you need a detailed plan of the steps you will follow, specified in enough detail that other investigators could carry out the investigation themselves. For example, if you are conducting interviews with people to determine the factors that make for likeability, you need to specify the questions you will ask in a survey or interview, how the respondents will be chosen and how the data will be collected. In surveys, you have to specify the layout and order of questions. In interviews, you have to specify the method of recording answers and the order in which the questions will be asked. In the party simulation, you need to specify how different actors will carry out the strategies so that there is replicability in implementing the strategies.

It is wise to check your plan to see how feasible it is to execute and whether it produces the kind of data you expect. The most common way to evaluate a plan is to conduct a pilot study with a few subjects over a short period of time. You do not have to analyze the pilot data carefully, but you should check to see that the data you are getting are reasonable. You should consider whether any changes in your plan are warranted on the basis of the pilot results.

When you carry out the investigation in full, you should look carefully at the results to see if they are plausible and consistent. You also need to determine whether the plan was executed as specified or whether there were problems that arose that caused the investigation to vary from the planned procedure.

Further Issues to Consider When Designing Investigations

Confirmatory studies, designed to confirm or test hypotheses, are best suited for situations where there are a small number of hypotheses and variables. When situations are complex, investigators may only be able to test a few specific predictions of a theory. Many confirmatory studies simplify or standardize the situation and collect a large amount of data, hoping that factors that have not been controlled are contributing randomly to the effects being investigated and will not affect the group averages in any systematic way. Another way to deal with complexity is to use multivariate methods, such as regression or covariance analyses. The intent in these methods is to control complexity by taking into account, through statistical adjustments, factors, other than those specified in the hypotheses, which might have effects on the results. The problem with these multivariate methods is that they depend on correlational evidence and ignore variables that are not quantifiable. Many verification studies, such as those using analysis of variance methods, simplify the situation in order to get enough constraint to establish a strong causal argument.

In exploratory inductive investigations, different methods and data sources are often used to cover the phenomena of interest in order to construct a more robust theory. Dewey (1910, Chapter 7) suggested three principles for regulating the observation and collection of data in forming "explanatory conceptions or theories" that are still wise advice today: (1) Care must be taken in differentiating between what is observed and what is inferred, so as not to jump to hasty conclusions about one's theory. (2) One needs to look for multiple cases to see how general one's conclusion is, but one also needs to look for contrasting cases in order to determine the factors that are critical to the conclusion. (3) One needs to look for exceptions and contrasts that may challenge one's initial conclusions and suggest others (which is similar to having control conditions in a confirmatory investigation). One often learns more from examining anomalous cases that do not have the expected features.

Characteristics of a Good Investigation

There are a number of characteristics that make for a good investigation:

- *Directness*: The investigation should be tightly linked to the phenomena being modeled. The more indirect the measures, the more likely that the data will not accurately reflect the real world (Frederiksen & Collins, 1989).
- *Replicability*: The investigation should be carefully specified so that other researchers can carry out the investigation and ideally find the same results. This is related to the generalizability of the results. The plan for the research should characterize the situations within which the same results can be expected.
- *Transparency*: The procedures should be readily understandable by other researchers so that they can evaluate how well the investigation addresses the claims made. Transparency is also critical so that other researchers can replicate the investigation.
- *Systematic*: The procedures should be carried out thoroughly and systematically so that the results found can be relied upon. This requires representative samples and careful measurement. The accuracy of the findings depends on carrying out the investigation in a systematic way.
- *Distinguishing*: For confirmatory investigations, the experimental design should test the hypotheses so that the findings will support particular theories or models

and rule out other plausible theories and models. Such investigations are labeled "crucial experiments."

- *Feasible*: The investigation should be possible to carry out by other investigators so that the results can be replicated. Ideally the experimental conditions should be easy to create and the instruments and resources needed widely available.

How Different Investigations Fit Together

There are three major ways that different investigations can relate to one another: (1) One investigation can replicate another. (2) One investigation can complement another in order to triangulate on the results. (3) An exploratory investigation can lead to a confirmatory investigation, which can trigger further exploratory investigation. We will briefly discuss each of these relationships.

No investigation is ever an exact replication of another. The situations will be different, the participants will be different, and the procedures will be different. Replications help to determine how general the results are by showing whether they hold up under all these differences. When different results are obtained in a replication, it leads investigators to question whether the original results were spurious or whether some critical difference between the two investigations led to the different results. So replication is critical to the progressive refinement of theory.

Triangulation is an important strategy when investigators are dealing with complex phenomena. The goal is to bring different methods to bear on the same phenomena. For example, an investigation about what factors make someone like another person might collect data from three different sources: surveys with a range of people, data on what strategies are effective at a simulated party, and structured interviews with people about their friendships and feelings toward others. Other kinds of data, such as ethnographic observation, would also be valuable in order to triangulate on the best theory.

We have argued that exploratory inductive studies help in constructing models and theories, whereas confirmatory investigations are used to test hypotheses that represent competing theories; however, the process is really cyclical. Often confirmatory studies, especially if they include collecting rich data, provide clues for further theory development through an embedded inductive investigation of those data. This can lead to theory refinement and suggests new confirmatory investigations that can further refine and test the theory. Thus in scientific inquiry, testing hypotheses deduced from theories and interpreting patterns in data to construct new theories are intertwined. This process is complex and depends on meta-knowledge of the forms of inquiry one is engaging in at a given time and how they are interrelated as one moves from one form of investigation to another. Meta-investigational knowledge also makes one aware of the pitfalls and limitations of the forms of investigation one is using at any particular time.

Meta-knowledge for Data Analysis

Different Data Analysis Methods

Data analyses are systematic procedures for examining the information obtained in an investigation. We classified investigations as either exploratory, confirmatory, or mixtures of both, so we can characterize data analysis methods the same way. In addition, we can classify them as qualitative or quantitative. In fact, most graduate schools in the social sciences offer separate courses for quantitative and qualitative methods, thereby treating them as distinct categories.

Although the methods for analyzing qualitative versus quantitative data may differ, we argue that the primary goals of the analysis remain the same. Thus data analyses can perhaps best be characterized by how they support these common goals: (a) coding and representing data to reveal patterns, (b) testing hypotheses, (c) inducing new theoretical models, and (d) considering the generality of the findings. Exploratory studies, in which the main goal is to develop a model that accounts for the findings, require the testing of hypotheses to induce the model. Confirmatory studies not only test hypotheses derived from existing models but also provide rich data usually that lead to new models or theories (which are often about underlying mechanisms).

In the following, we illustrate some different data analyses by describing how data from the three studies we outlined previously, in the section on investigation, could be analyzed.

Study 1. Qualitative and Quantitative Exploratory Analyses Based on Interviews with Students About Their Views of Friendship

Data for this exploratory study are the tape-recorded answers students have given to the open-ended question: What is it about people that makes you like them? Analysis steps one can take are as follows:

Represent students' responses through data coding. In coding, one seeks to create as short a list of attributes as possible, which still covers all of the ideas that are mentioned by the respondents. What results is a set of "emergent" categories to capture the range of ideas expressed by students in responding to each question. The categorized data are recorded in a data table that indicates, for each student, which attributes were mentioned and which were not. A code book is also produced that provides examples of responses given each code category. The same codes are used for every respondent so that you can make comparisons among them.

Represent data in ways to see patterns. Create bar charts showing the percentage of students mentioning each response category to see what are the most frequent attributes mentioned by students. Also, try to determine which attributes "go together" in the respondents' answers to the two questions.

Use the patterns in the data to build a model. Having identified the relevant attributes, one might construct a multifactor model. By identifying which attributes go together, one can identify factors that interact in the model.

Consider the generality of the findings. The statistical tests of differences among frequencies of categories will give an indication of the likelihood that one would find similar results if the study were repeated with a new, comparable set of respondents. However, the investigation method used (asking questions of respondents) limits one's ability to claim that these results have been shown to apply to real-world friendship formation.

Explore the data to get ideas for follow-on analyses or investigations. As you study the data, you might notice, for instance, that some attributes of friendship seem to be mentioned more often by boys or girls. You could test this hypothesis by looking at frequencies of categories separately for each gender. As you build your multifactor model, you might think of new ways to test your model. For instance, you might decide to ask respondents questions about particular friends, instead of friends in general, to see if the same attributes are important for different people.

Study 2. A Quantitative, Confirmatory Analysis to Test Hypotheses About Strategies for Making Friends

This proposed investigation sought to test elements of the multifactor model using a "party" simulation. Imagine that actors were chosen to adopt different strategies for making others like them, such as (1) flattery, (2) common interests, and (3) amusing stories. For each strategy, there were a number of actors. Each group of actors was chosen to be equally appealing a priori, on average. The people at the party circulated and talked to all of the other people, including the actors (they were not aware that there were any actors at the party). After they talked to each person, they rated the actors on likeability using a five-point scale. In order to get reliable data, the procedure was repeated with three different groups of people, with each actor using a different strategy at the three parties.

Enter data into a data table. For each actor using a particular strategy, his/her rating should be entered into a data table. The data table should use a systematic design, so it will be easy to analyze using a statistics program or spreadsheet.

Represent data in ways to see patterns. Calculate the average likeability for each strategy and actor. Look to see if any one strategy was better than any others and make a bar chart of the means for each strategy and actor.

Test hypotheses. Calculate the mean rating for each strategy. If the pattern of differences among strategies is consistent with any of the hypotheses, you can have increased confidence in the model that generated that hypothesis. If the results are not consistent with any of the hypotheses, think about why. Is the model inadequate? Are there things going on in the study that the model did not anticipate?

Consider the generality of the findings. For each person, calculate the mean likeability for the actors who used each strategy. Then do a statistical comparison of the means for each strategy using analysis of variance or *t*-tests. If there are significant differences among them, there is evidence of generalizable trends for this population.

Explore ideas for follow-on investigations. In order to get a better idea of the reasons why people liked, or did not like, the actors who used particular strategies, one could interview the participants and ask them about their reasons for liking or not liking each actor.

Study 3. Qualitative and Quantitative Exploratory Analyses Based on Observation of the Development of Friendships Within a Book Group

This is a study of how groups of friends evolve over time in an actual social group, here, a book group made up of people who do not know each other beforehand. The goal is to construct an agent model that embodies the interaction patterns. Regular meetings of the book group would be videotaped, and interviews would be conducted with each participant shortly after each meeting. The interviews might ask (1) How do you feel about X and why? (X = each person)? (2) Did you do anything to make others like you? (3) Did you do anything to attract or put off X and if so what? The research questions could be the following:

- What factors determine how much each person likes another?
- What strategies do people use to attract or put off others?
- How do their relationships change over time?
- Do cliques form and change over time? What is the process of clique formation?

Code the data. Code the interview data and enter the results into a data table, as described for study 1. Code the interactions among all participants shown in the videotapes of book group meetings. One way of coding the data is to consider each person and code their interactions with other members of the group (this is the unit of analysis). Things one might code are (a) Who are they addressing/commenting on? (b) Are they interrupting? (c) What is their emotional tone (e.g., smiling, nodding, grimacing, sighing)? (d) Are they agreeing or disagreeing? (e) Are they building on, ignoring, or contesting the other's ideas?

Represent data in ways to see patterns. One goal is to identify closely interacting groups (cliques) based on observations of interactions among individuals. Cluster analyses could be carried out using different kinds of data, such as positive interaction time and negative interaction time, the frequency of positive versus negative interactions, and the positive feelings for each member expressed in the interview. Groups could be identified for each meeting of the book group so that one could look at changes in clique memberships. Another goal is to identify the precursors of clique formation in terms of the kinds of interactions members have in prior meetings. One could also look at the interview response codes for the same interactions, such as the strategies people used to attract others.

Build a model and explore its ramifications with further data analyses. These data analyses will provide a rich array of information about factors that contribute to forming friendships in a new social group. The model is constructed by developing various hypotheses about critical factors and determining whether they apply across different circumstances. If they do, they become part of the model. Considering implications of the model will lead to additional questions and, often, to further hypotheses about factors that might be observable in the data at hand for the study.

For instance, new criteria for video analysis might be suggested, which could then lead to additional data analyses in which these hypotheses are tested.

Consider the generality of the findings. Since the study used only one social group (the book group), data are not available to empirically test the generality of the findings for other kinds of social groups that might be constituted. However, an argument for the plausibility that the results are generalizable can be made based on the typicality of the group used in the study.

Purposes of Data Analysis

The main purpose of data analysis is to support the development of convincing arguments, which show how the findings from an investigation support particular conclusions and have implications for theories. Date analyses examine the information obtained in an investigation in order to meet several objectives in developing and testing models and theories. These include the following:

(1) *Creating representations that will reveal patterns*: One objective is to code and display data in ways that summarize the data and reveal patterns. Achieving this goal requires what diSessa terms meta-representational expertise (see diSessa, 2002a, 2002b, 2004).

(2) *Interpreting how data provide evidence with respect to competing hypotheses*: A second objective is to use patterns found in the data to determine which hypotheses are supported or refuted by the data. These may be hypotheses that were predicted ahead of time, using existing models (confirmatory studies), or that emerge from the data to construct new models (exploratory studies).

(3) *Exploring the data to develop new models, theories, and ideas for further research*: Another objective is to search the various representations of the data for unanticipated phenomena or relationships among variables. Discoveries made through this process may lead to modifying an existing model or to creating new models and theories. This, in turn, leads to further research to investigate the utility and generality of the new model.

(4) *Establishing the generality of the findings*: A final purpose of data analyses is to provide evidence regarding the generality of a theoretical model—the range of circumstances to which it applies. If there are limitations to the conclusions one can draw about the model's generalizability, this can lead to adding boundary conditions to the model or to revising it. Alternatively, it may lead to suggestions for further research in order to more adequately determine the generalizability of the model.

Pursuing these objectives leads to data analyses that enable one to develop and test theoretical models, as well as to improve the range of coverage and explanatory power of a theory.

Creating Analyses

Coding data. In developing ways of coding data, one should think about what features of the data need to be represented to test existing hypotheses and develop new ones. Sometimes these features are not immediately available in the data and need to be inferred or coded. This is most often the case when the data are qualitative, such as when they are based on participants' responses and are coded using categories or abstracted descriptions.

In order to see patterns, data obtained in different situations need to be represented using similar measurements or coded qualitatively using similar categories. This makes it possible to make comparisons of data across different situations. Coding of variables may be based on either predetermined aspects of responses, or they may be "emergent" categories based on examining all responses and creating categories that distinguish them in theoretically interesting ways.

Representing data to reveal patterns. Ways of representing data need to be devised that will (a) indicate whether patterns predicted by a hypothesis or model are present, (b) reveal unexpected patterns that may require modifications to the model, or (c) reveal patterns that lead to the induction of a new model. The goal in each case is to display relational features of the data that show what is "going on" and thereby provide a way of testing the explanatory power of competing theories. Tools used to represent data include statistical ways of describing data (e.g., means or frequencies for different situations) and graphic tools for visualizing relations (e.g., bar charts, scatter plots). Experience and education in data analysis techniques will lead to creating a "library" of forms for displaying data (cf., Giere, 1991). For instance, a graph of average values obtained before and after a treatment, shown for two different treatments, may be a good way to see if there is an interaction between treatment and effect in a confirmatory study.

There are many kinds of patterns that can emerge from data, paralleling the many kinds of relations among variables that are generated by different types of models. In complex, multivariable data sets, the number of pair-wise relations among variables can be great, and the possibility of interactions among variables increases the number of possible patterns even further. Exhaustively searching for all meaningful relationships is often impractical. Thus the particular techniques used in data analysis to reveal patterns are often guided by the epistemic forms of the models one is trying to create and test. The choices of epistemic forms and data analysis methods interact: you see data patterns through analyses that are themselves suggested by theoretical models. In arguing for a particular interpretation of data, you need to be cognizant of how other investigators with different theoretical orientations might interpret the data. One of the most difficult things in data analysis is to be able to "put on the hat" of a different theorist and consider alternative forms of analysis and types of models which they might entail.

Testing hypotheses. If the investigation is a confirmatory study, then the predictions made by the competing hypotheses need to be tested against the data. Similarly in exploratory studies, one generates hypotheses that need to be tested. For each hypothesis, one reviews the summarizations of the data, created in the previous step, to see if the hypothesis appears to be supported or refuted. Investigators often use both descriptive and inferential statistics to do this. In carrying out this step, you must be sure to identify patterns that disconfirm predictions of the underlying theory, or that were not anticipated, in order to see which aspects of the model need to be replaced or improved or if the whole way of thinking about the phenomena needs to be reconsidered.

Patterns can thus be found in data that provide evidence for whether a hypothesis is confirmed or disconfirmed. Confirming a hypothesis increases confidence in the theory's accuracy, but does not confirm the theory itself, because other theories might be constructed that lead to the same prediction and hypothesis. However, disconfirming a hypothesis can support an argument for rejecting the associated theory. Popper (1963) argues that strong theories are subject to refutation when tested, but can never be fully confirmed. Theories that are not fully specified are hard to disconfirm, because they can be augmented to account for factors that had been left out. Having such meta-knowledge about the relationship between theory and evidence should help investigators make appropriate inferences from their data about the status of their theories. It should also lead them to create theoretical models that are increasingly well specified as their research progresses.

Creating new models. If the investigation is an exploratory study, then one is using the data to develop new theoretical ideas. Also confirmatory studies often produce findings that were not predicted by any of the hypotheses and that require a new theoretical model. In creating a new model, you need to incorporate concepts and relationships that predict and account for the patterns found in the data analysis. Choosing the type of model, or epistemic form, will determine more specifically what is needed from the data analysis, such as what type of patterns need to be identified (Collins & Ferguson, 1993).

Finding evidence of generalizability. Theoretical models are expressions of relationships that have general applicability across a range of situations. In scientific inquiry, establishing the generality of a model is important. Commonly, one obtains data from a sample of different situations, or individuals, to provide evidence for the consistency of the results that are predicted by the model across the range of circumstances to which it purportedly applies. However, a theoretical argument for the generalizability of a model to other situations can also be made. This can take the form of specifying the conditions that are necessary for a model to apply, with the implicit suggestion that other factors not mentioned are irrelevant. Such theoretical arguments lead to further research.

When interesting patterns are found during data analysis (e.g., that support or refute a hypothesis or that suggest a new model), there is a need to determine that the patterns are not "flukes," but are reproducible over a range of instances that the model purports to cover. Often this involves studying a sample of similar situations and determining statistically that the patterns have occurred too regularly to have happened by chance.

Emerging ideas for follow-on investigations. Exploratory studies lead to the creation of theoretical models that require further investigation. In confirmatory studies, a careful and deep data analysis often leads to many new questions and hypotheses for future investigations. In addition, the data analysis will suggest many ways in which the investigation could be improved. For example, the investigator may discover factors that were not controlled or may think of different situations that could have been studied.

Characteristics of a Good Data Analysis

In carrying out a data analysis, the desirable characteristics that should drive the analysis include the following:

- *Perspicuous*: The representations of the data should organize and summarize the data in productive ways, so one can see the patterns.
- *Complete*: The analyses should test all reasonable hypotheses in order to be thorough and complete.
- *Systematic*: The analysis procedures should be carried out carefully and systematically.
- *Accurate*: The analysis needs to avoid miscalculations and violation of the assumptions inherent in the methods used.
- *Coherent*: The interpretation should fit all of the data in an integrated way and be consistent with other known sources of data that are pertinent.
- *Transparent*: The analysis procedure should be easily understood and replicable by other researchers.

How Different Analyses Fit Together

As we illustrated in this section, analyzing rich sets of data can allow researchers to test specific hypotheses and develop new theoretical models. This applies, as we have argued, whether the study is primarily exploratory or confirmatory. Often this means collecting both quantitative and qualitative data about a phenomenon. The best analyses involve displaying the data in different forms so that different patterns can be seen. The different patterns then can be tested for statistical significance or for consistency across cases, which can lead to supporting or revising an existing model or to developing new theoretical models. Ideally researchers should be able to synthesize findings from all of their analyses to produce a coherent interpretation that supports a particular theory, one that provides a better account of the data than other competing theories they considered. This can involve, for example, testing causal models, perhaps using inferential statistics, while also analyzing the data to develop process models of the underlying mechanisms. The resulting theory would thus incorporate models that provide both causal and mechanistic accounts of the phenomena being studied.

Discussion

Summary of the Meta-knowledge Framework

We have proposed a framework for scientific meta-knowledge in terms of four primary processes and various supporting processes. The four primary processes are (1) theorizing, (2) questioning and hypothesizing, (3) investigating, and

(4) analyzing and synthesizing the findings. The supporting processes include cognitive, social, and metacognitive processes (see White & Frederiksen, 2005), including regulatory processes that guide scientific inquiry (see White et al., 2009). We developed a standard form for characterizing each of the four primary processes in terms of five elements: (1) the different types, (2) the purposes, (3) the creation process, (4) the criteria for evaluation, and (5) the synthesis of the different types. This is the basic structure of the framework.

With respect to theorizing, we discussed three different epistemic forms or model types: (1) structural models, such as a stage model, (2) causal models, such as a multifactor model, and (3) process models, such as an agent model. We illustrated each of these types in terms of simplified models of friendship. Stage models show how events unfold over time. Multifactor models specify all the factors that influence a particular dependent variable. Agent models allow one to simulate the process of interaction among a set of different actors. Different types of models can serve to embody different parts of an integrated theory, such as a theory of friendship.

Generating research questions is the process that bridges from theory to designing an investigation. Different types of models generate different kinds of research questions. For example, stage models ask how many different phases or stages there are, what are the characteristics of each stage, and what leads to the transition from each stage to the next. Multifactor models raise questions about what factors affect the dependent variable, how the factors are causally connected to the dependent variable, and how the factors combine to affect the dependent variable. Hence, research questions are linked together by the type of model being developed and investigated. Hypotheses constitute the possible answers to the research questions posed and may be derived from competing models and theories.

Investigations can either be exploratory or confirmatory. There are many ways to conduct exploratory studies, such as by carrying out discourse or protocol studies or studies using observational, interview, and survey methods. There are also different forms that confirmatory investigations take, such as randomized controlled trials, where hypotheses are tested by assigning subjects randomly to different conditions and then comparing how the subjects perform. The kind of data collected has a strong effect on the types of models that can be constructed from the data. For example, quantitative data support construction of multifactor models, as in the Framingham Heart Study. To construct process models, such as agent models, one needs a richer data stream, such as observational, protocol, or discourse studies provide. These models can then be evaluated using confirmatory methods.

Analysis and synthesis use data from an investigation to arbitrate between competing models and to develop new models. There are four aspects to this process: (1) coding and representing data to reveal patterns, (2) interpreting the patterns with respect to competing hypotheses, (3) exploring the data to induce new models, and (4) determining the generality of the findings. With qualitative data, a coding scheme helps to create useful data representations. In order to see patterns in the data, there are a variety of representational tools, such as graphs, charts, and computer-based visualization tools. Statistical tests can be applied to help determine relationships in the data, as well as to determine the generalizability of the findings. Often surprising patterns may be found in the data, which suggest revisions to models or lead to new theoretical models, further investigations, and more data analyses.

Teaching Scientific Meta-knowledge

To develop and demonstrate an understanding of the four kinds of scientific meta-knowledge that we argue are needed, students would need to engage in an extensive inquiry curriculum, one aimed at developing and testing models of different types, which would fit together to create a scientific theory for a given domain. For each study they undertake, students would need to consider which type of model they want to develop, which type of question they should ask, which type of investigation they need to carry out, and which data analysis techniques they should employ. Being able to make such decisions presupposes that they know about different model types, question types, investigation methods, and data analysis techniques and, further, that they know how these work together to create and test scientific theories.

While our Inquiry Island and Web of Inquiry software embody much of the meta-knowledge we have described in this chapter, our own research program has provided limited opportunities for determining how best to teach such meta-level expertise to young students (i.e., upper elementary and middle school students). In one attempt to develop students' meta-modeling knowledge, for example, we designed a version of our ThinkerTools Inquiry Curriculum that focuses on enabling students to learn about different types of scientific models and their utility (Schwarz & White, 2005). The results were encouraging, though the impact of the curriculum was strongest on the higher achieving students.

In most of our recent work (Frederiksen et al., 2008; White & Frederiksen, 2005), the teachers we collaborate with only commit to having their students engage in one or two major research projects per year. Given this limited time commitment, we have focused on enabling students to develop a particular type of theory, which usually consists of a causal model (often multifactor) linked with some preliminary models of underlying mechanisms. To evaluate their theories, students design and carry out a particular type of investigation, usually a controlled comparison designed to test their competing hypotheses. They then undertake a limited range of data analyses, typically centering around a comparison of averages and frequency distributions of data from the various experimental conditions. Thus, although the students learn a great deal about scientific inquiry and produce some impressive research projects (Frederiksen et al., 2008), the restricted instructional time and number of investigations students undertake limit the development of their meta-level expertise.

Creating curricula that adequately teach scientific meta-knowledge would require a much more extensive curricular sequence that would give students opportunities to learn more about different types of models, investigations, and analyses, as well as how all of these components of inquiry work together, throughout a series of investigations, to create comprehensive scientific theories. Engaging in such a curriculum would thus necessitate a serious time commitment on the part of schools and teachers. Teachers, along with those who develop curricular standards and accountability measures for science education, need to be convinced of the importance of scientific meta-knowledge.

Concluding Thoughts About the Utility of the Framework

A major benefit of the meta-knowledge framework described in this chapter is to increase the awareness of students, teachers, and scientists as to different types of models, questions, investigations, and analyses. If they have a toolkit that includes a wide variety of model types, they may construct richer theories by building multiple models of different types and linking them together. Similarly if researchers learn how to use different investigation methods, they can combine these methods to triangulate on the phenomena they are trying to understand and hence produce more robust results. The framework provides guidance to make informed decisions as to what to do at different points in the inquiry process. Our basic argument is that scientific meta-awareness provides insights for scientists and students that will enhance their ability to learn and understand scientific inquiry.

One long-term goal of our work has been to develop computer-based tools that support scientists and students in their work. For example, we think a modeling tool could help scientists construct many different kinds of models, just as Stella (High Performance Systems, 2000) helps students construct system-dynamics models and Net Logo (Wilensky, 1999) and Agent Sheets (Repenning, Ioannidou, & Zola, 2000) help students construct agent models. Such a tool could help scientists and students consider different types of models they might construct and provide a structure, which guides the development of each type of model.

Inquiry Island and the Web of Inquiry provide another kind of computer-based tool that can support scientists and students in their research. Inquiry Island has extensive advice about the issues people should address as they construct models and theories, formulate research questions and hypotheses, carry out investigations, and analyze and synthesize the data they collect. This advice is available when people ask for it or when they appear to need it. It can be modified, in the Web of Inquiry, for particular types of inquiries or for particular groups of people. The goal is to refine Inquiry Island and the Web of Inquiry as general-purpose tools that can support scientific inquiry at many different levels.

Clearly more work remains to be done. This chapter only presents a top-level view of the kind of meta-knowledge we think is central to scientific inquiry. For example, there are many different kinds of model types or epistemic forms (Collins & Ferguson, 1993) that scientists and students might learn to use. In fact, artificial intelligence has led to a proliferation of different model types in its short history, such as production-system models, agent models, constraint-satisfaction models, semantic-network models, frame-system models, qualitative-process models. This proliferation of model types provides new power for making sense of diverse phenomena in the world. Understanding the affordances and constraints in building models of these different types should become a learning goal for future scientists.

Such work on meta-scientific knowledge should thus have benefits that go beyond science education. We think that our framework provides a structure that will enable science to refine its practices and products. Making the meta-knowledge underlying scientific processes explicit fosters systematic reflection by scientists and the field as a whole. This reflection enhances the possibility that a self-improving system will take hold to develop better tools, models, and representational forms. Hence we argue that the development of an explicit understanding of the nature of scientific meta-knowledge will lead to a more productive scientific enterprise.

Acknowledgments This research was funded in part by the National Science Foundation (grants MDR-9154433, REC-0087583, and REC-0337753). We thank the members of our research team for their contributions to this work, as well as the students and teachers who participated in our studies. The views expressed in this chapter are those of the authors and do not necessarily reflect those of the National Science Foundation.

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Chapter 4
From Modeling Schemata to the Profiling Schema: Modeling Across the Curricula for Profile Shaping Education

Ibrahim A. Halloun

Research has been undertaken for the last 4 years, in part under the auspices of Educational Research Center, to extrapolate the work on modeling theory in science education (Halloun, 1984, 1994, 1996, 1998a, 1998b, 2000, 2001, 2004a, 2004b, 2004/2006, 2007a, 2007b, 2008) into the broader field of education. Profile Shaping Education (PSE) has emerged in the process as a generic educational framework that may be deployed in designing and deploying various curricula. PSE calls for any systemic effort in education to empower the target population (e.g., students, preservice and in-service teachers, administrators) with a particular profile following well-established pedagogic principles and rules (or general and operational standards), and in accordance with well-defined cognitive, metaphysical, and educational tenets. The target profile can be readily translated, using a particular profiling schema, into measurable outcomes which would be reified in various course materials, and ascertained in various forms of assessment. This chapter discusses, in the context of PSE, the development of the profiling schema in question, beginning with its origins in modeling theory, and its implementation in certain educational programs, especially the International Arab Baccalaureate (IAB).

Modeling Theory in Science Education

The work of this author on modeling began in physics as part of his Ph.D. dissertation at Arizona State University (Halloun, 1984). Through classroom-based research, scientific models and modeling were originally transposed from professional tools and methodology of scientific research into pedagogical tools and methodology for learning physics meaningfully at the college level (Halloun & Hestenes, 1987; Halloun, 1984). Subsequently, and as an integral part of this author's drive for a "modeling theory in science education", models and modeling gradually evolved into generic pedagogical tools and methodology for meaningful

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_4,

development of any scientific paradigm at any school or university level (Halloun, 2001, 2004/2006, 2007a). Unless otherwise specified, any mention in the following of "models", "modeling", and "modeling theory" refers to this author's perspective on these matters as summarized below and as reflected in his work for the pedagogical theory in question.

Modeling theory calls for any science course to help individual students bring their personal paradigms, often governed by naive realism as educational research showed in the last three decades, into a state of relative *commensurability* with scientific paradigms. A paradigm consists, for us, of major *tenets* (i.e., metaphysical or foundational statements, often of axiomatic nature), *principles* and *rules* that govern development and deployment of certain *habits of mind* (cognitive processes and dispositions) and *episteme* (a body of conceptions or conceptual knowledge). A scientific paradigm is a paradigm accepted and shared by a community of scientists. The corresponding episteme consists of a corroborated scientific theory or set of interrelated theories, with each theory primarily consisting of a set of scientific models and appropriate principles and rules for model construction and deployment. A *scientific model is a representation of a specific pattern* in the real world, and *modeling involves habits of mind for model construction, corroboration, and deployment*. The pattern may be about the structure and/or the behavior of a number of physical systems in the universe. Scientific habits of mind include generic cognitive processes (skills) and dispositions (values, attitudes, and other meta-cognitive controls) which scientists systematically invest in the construction, corroboration, and deployment of scientific theory, models included.

Modeling theory calls on teachers to empower students to resolve, explicitly and to the extent that is possible in a given science course, epistemic and cognitive incommensurability between naive paradigms and corresponding scientific paradigm(s), while mediating construction and deployment of scientific models. When students are guided in this direction in the framework of modeling theory, comparative research shows that they become more effective problem solvers (Taconis, Ferguson-Hessler, & Broekkamp, 2001) and that their overall course achievement becomes significantly better under the prescribed modeling approach than under any other form of instruction, especially traditional instruction of lecture and demonstration (Hake, 1998; Halloun, 1984, 1994, 1996, 1998a, 1998b, 2000, 2004a, 2007a, 2007b; Halloun & Hestenes, 1987).

The advocated approach owes its relative success to the fact that it focuses on both course content and instructional methodology, without compromising one for the other, and in ways that bring the foundations of scientific paradigms into consonance, even resonance, with the foundations of human cognition. This is achieved, in part, in the manner outlined in the following six sections.

Paradigmatic Perspective

Under modeling instruction, students are guided to develop any conception (concept, law, or any other theoretical entity or statement) or habit of mind (process, skill, or disposition about knowing or learning science) from a paradigmatic perspective, and not in an episodic, piecemeal approach. In such perspective, any learning activity is conducted in the context of the big picture defined by the scientific theory that conception and habit are about, and in accordance with epistemological, methodological, and axiological tenets associated with the paradigm which the theory belongs to.

Epistemological tenets, to which we subscribe, postulate that there are patterns in scientific knowledge, just like there are patterns in the physical world. In this world, patterns manifest themselves in the structure and behavior of physical systems, but especially in the conservation or change of state of such systems while interacting with each other. Patterns in the scientific realm are best manifested through scientific models, with each model representing a specific pattern in the structure and/or behavior of physical systems, and making part of a particular scientific theory that sets the scope and structure of the model in accordance with well-defined paradigmatic principles and rules.

Methodological and axiological tenets we subscribe to are primarily those that govern model construction and deployment (corroboration included), and that allow students, in the process, to efficiently develop scientific habits of mind, and ingrain them constructively and productively in their individual mental profiles.

Under modeling instruction, students are constantly engaged in the development of scientific models of increasing level of complexity in accordance with the tenets above. Furthermore, a balance is maintained in the process between the epistemic dimension (conceptions) and the cognitive dimension (habits of mind), with special attention to the latter since habits allow meaningful development of conceptions more than the other way around. Special attention is also devoted to reflect the generic aspect of all habits of mind, as well as of some basic conceptions in scientific paradigms, in ways to allow students realize and appreciate cross-disciplinarity among various scientific fields, as well as between those fields and nonscientific fields. As a consequence, students begin to think coherently and efficiently, and learn course materials meaningfully and productively, especially when they are empowered to take advantage of knowledge (conceptions and habits of mind) developed in one course in other courses and in everyday life.

Critical Thresholds

A number of *thresholds* are defined within every scientific theory that set (a) a paradigmatic hierarchy in the structure of the theory, and especially (b) an efficient cognitive and pedagogical sequence in the scope of any scientific course which the theory is about. The most critical of these thresholds are the "basic threshold" and the "mastery threshold" (Fig. 4.1). The basic threshold is set between the *core* body of knowledge and the *fundamental* body of knowledge. Core knowledge corresponds to a limited number of the most *basic models* in the context of which, from a pedagogical perspective, can be developed the most fundamental and critical conceptions and habits of mind of the corresponding scientific theory. Fundamental

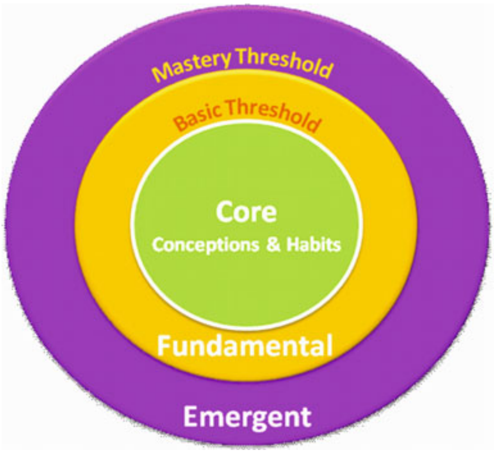

Fig. 4.1 Critical thresholds in the structure of scientific theory, as set from paradigmatic and pedagogic perspectives

knowledge embodies somewhat more complex *basic models* in the context of which students reinforce, and widen the scope of, core conceptions and habits, and derive from them new conceptions and habits. Emergent knowledge typically involves models that may emerge from the composition of two or more basic models, as well as original, more complex models.

A student needs to meaningfully develop the *entire* core knowledge before s/he can proceed to fundamental knowledge. Any flaw in developing any conception or habit of mind in the core knowledge prevents the student from crossing the basic threshold, and thus from developing fundamental knowledge meaningfully. Students normally require significant teacher mediation, in the form described below under modeling instruction, in order to reach such threshold. Once they cross it, teacher mediation can be gradually reduced throughout the fundamental body of knowledge until students cross the mastery threshold. Beyond that threshold, students should be capable of developing the more complex emergent knowledge with the least teacher mediation ever.

For example, in Newtonian theory of mechanics, core knowledge corresponds to the most elementary two *basic particle models* in the context of which students need to develop all basic concepts and laws of Newtonian kinematics and dynamics, as well as basic habits of mind necessary for model construction and deployment. These models are the free particle model representing physical objects in translation with constant velocity under no net force, and the uniformly accelerated particle model representing physical objects in translation with constant acceleration under a net constant force. Fundamental knowledge, in a typical senior secondary school course or freshman college (university) course, involves either or both types of *basic particle models*: bound particle models (circular or simple harmonic motion), and particles interacting with impulsive forces (collision). Emergent knowledge may encompass, in such courses, other types of bound particle models, as well as particle models of objects interacting with velocity-dependent (friction, drag) or time-dependent forces.

Similarly, core knowledge in introductory calculus courses includes three functions (and related differentiation and integration). These are the linear function, $y = ax + b$, the quadratic function, $y = ax^2 + bx + c$, and the linear fractional function, $y = (ax + b)^{-1}$. These functions are *basic* from both mathematical and scientific perspectives. From mathematics perspective, linear and quadratic functions are most foundational. From these two lower-order functions emerge other power functions. They are most adequate for students to develop basic aspects of functions, especially rate of change and covariation. In addition, the linear fractional function is important, yet simple enough, for students to develop an understanding of the domain of a function and of asymptotic limits. From science and engineering perspective, the three types of function are simple, yet powerful enough, to allow students to develop basic understanding of how a function allows description or explanation of a given pattern in the structure or behavior of some real-world systems.

As for the basic threshold, it pertains in the case of functions to the process of covariational reasoning about functions in the context of concrete, everyday life situations and other science-related empirical situations. This threshold embraces, among others, cognitive processes required to (a) tease out primary variables, (b) identify patterns of change (or conservation) in individual variables, (c) coordinate the change of a dependent variable (y) with one independent variable (x) over a range of values of x (dynamic covariational reasoning about a pattern), instead of associating one value of x at a time with one value of y (localized association game via the input–output machine metaphor), (d) spell out a formal functional relationship between the two variables, (e) use and interpret particular representations of a function, (f) coordinate among distributed representations of the function, and (g) deploy the function in novel contexts.

Modeling Schemata

Modeling schemata have always been the most critical factor underlying students' success under the modeling approach. These schemata are generic tools that may be used by teachers for lesson planning and implementation, and by students for systematic construction and deployment of scientific conceptions, especially models. The most important schema originally defined in modeling theory was the model schema.

The *model schema* is a four-dimensional template for putting together any scientific model, at least those models that are the object of study in secondary school and college science. Two of the four dimensions, composition and structure, set the ontology and function of the model, and the other two, domain and organization, set its scope, all in terms of the scientific theory which the model belongs to, and by correspondence to physical realities revealing the modeled pattern.

The *domain* of a scientific model includes all physical systems manifesting the pattern which the model represents. A model's domain is delineated by specifying those systems, as well as the conditions under which the model can represent the pattern in question, and the corresponding limits of approximation and precision.

Model *composition* consists of concepts representing *primary* constituents and respective properties of physical systems, i.e., only those constituents and properties that are salient to the pattern. Explicit focus on model composition is meant to help students discern between primary and secondary aspects of a pattern, i.e., between those aspects that need to be accounted for in the modeling process and those that may be ignored within the considered limits of approximation and precision. In model composition, primary object and property concepts are only listed and not related to one another.

Model *structure* spells out relevant relationships among primary features (constituents and their properties) of the pattern represented by the model. Model structure can be defined along four subdimensions, or facets, each dealing with a specific aspect of the pattern. These are the topology facet, the state facet, the interaction facet, and the cause–effect or causal facet. Each facet comes primarily in the form of laws that help setting the distinctive descriptive and/or explanatory *function* of the model. The topology facet specifies what entities the model consists of (e.g., particles or solids in mechanics) and how these entities are positioned in a given reference system. The state facet spells out state laws that *describe* the behavior of each entity (e.g., kinematical equations of motion). The interaction facet consists of interaction laws that govern how various entities interact with each other (e.g., Newton's law of universal gravitation and Hooke's law). The causal facet provides cause–effect laws that *explain* the behavior of each entity (e.g., Newton's second law).

Model *organization* situates a given model in the respective scientific theory. It establishes the potentials and limitations of the model, and relates it to other models in the theory (showing differences and similarities). It also sets rules for extrapolating the model in the construction of new models within and outside the scope of the theory in question.

A similar schema was originally defined for *concept* construction and deployment. As we shall see below, various modeling schemata have evolved recently into a single, generic schema that may be deployed in any educational field and not only in science.

Progressive Middle-Out Approach

Models are at the center of what we call *middle-out* epistemic and cognitive structure of scientific paradigms. They are in the "middle" of conceptual hierarchy, between theory and concept. A scientific model is to theory and concept what an atom is to matter and elementary particles. Each elementary particle is essential in the structure of matter, but its importance cannot be conceived independently of its interaction with other particles inside an atom. It is the atom and not elementary particles that give us a coherent and meaningful picture of matter, and it is the atom that displays best the role of each elementary particle in matter structure. As such, models (a) ensure a cohesive structure of scientific theory, and (b) constitute the most accessible, efficient, and reliable building blocks in knowledge construction and deployment. Models subsequently ensure theory and paradigm coherence and consistency from an epistemic perspective, and they facilitate development of scientific knowledge from a cognitive perspective.

Modeling theory calls for the development of any course of science in a middle-out approach from both epistemic and cognitive perspectives. Accordingly, (a) all target conceptions at any level, especially in the core knowledge, are supposed to be developed as building blocks of corresponding models, and not as self-contained entities, and (b) all target habits of mind are meant to be developed in the process, beginning with subsidiary models. A *subsidiary model* is a simplified version of a target scientific model, a particular case which students may usually be most familiar with, and which can serve as a stepping-stone for the comprehensive construction of the target model.

For example, a particle in free fall (objects falling in vacuum in the absence of any force except for gravity) may serve as a subsidiary model of the uniformly accelerated particle model in Newtonian theory. To construct the latter model, students may begin resolving any incommensurability between their own ideas about free fall and the Newtonian perspective on this type of translation. They would then gradually develop this subsidiary model restricted to the case of linear motion in a constant gravitational field, and extrapolate it into the broader case of parabolic, uniformly accelerated motion under any type of a net constant force (or field). The subsidiary model in question would thus serve, at the lower end of the middle-out hierarchy, to develop or refine conceptions and habits required for the particular instance of free fall, and, at the upper end, to extrapolate the subsidiary model into the construction of the target uniformly accelerated particle model. Meanwhile, habits of mind developed, and/or refined, in the context of the subsidiary model, would be gradually decontextualized in the process, so that students may subsequently deploy them into more complex situations within and outside the context of the course in which they are enrolled.

Experiential Learning Cycles

Under modeling instruction, students are constantly engaged in a variety of hands-on, minds-on modeling activities that help them develop scientific conceptions meaningfully, and scientific habits of mind productively. All activities are conducted within well-structured learning cycles. A learning cycle is, for us, a modeling cycle, a cycle for model construction and deployment. Each cycle begins with an exploration phase whereby students discover the potentials and limitations of knowledge (models) they have developed so far, and realize the need to construct a new model that represents a specific pattern. Students are then directed to formulate appropriate hypotheses about the desired pattern, i.e., to propose a candidate model, and design and implement an appropriate strategy for testing their hypotheses. The strategy would take them into a process of gradual corroboration and progressive refinement of the proposed model. At certain points during the process and afterwards, students deploy the model in order to consolidate it and relate it to other models within the context of the theory which all these models belong to.

In all activities, students follow an *experiential* approach that involves a variety of *dialectics* within and between two worlds, the *empirical* world of physical realities and related data, and the *rational* world of students' own realm and/or the scientific realm. Students thus develop their epistemic and cognitive knowledge through interaction, or rather transaction in Dewey's sense, with empirical data. This is in contrast with *traded knowledge* that one learns *about*, mostly at face value, and by rote, from other people, from textbooks or any other medium of information dissemination.

Modeling activities are diversified so as to help individual students develop a balanced diversity of habits of mind pertaining to *exploratory* inquiry and *inferential* inquiry, on the one side, and *innovative* research on the other side. Exploratory inquiry may involve description or explanation of existing realities (systems and phenomena), and inferential inquiry may involve prediction or post-diction of the future or past evolution of such realities. Both types of inquiry do not involve any conscious or deliberate interference by the observer in the state of systems under inquiry. Innovative research involves such interference in order to reify a model (a pattern) through control or change of existing realities or through design and construction of new realities.

Appropriate dialectics are prescribed within and between the rational realm and empirical world in all three types of activities in view of helping students resolve any incommensurability between their own paradigms and scientific paradigm(s). Rules of engagement may somewhat recapitulate the historic development of scientific paradigms in the manner discussed below.

Mediated Regulation

Modeling instruction is student-centered, teacher-mediated. It is student-centered in the sense that it engages individual students actively in the learning process, but it does not leave them out entirely on their own free will. Any course has a specific agenda to fulfill: meaningful and insightful paradigmatic evolution within the confinements of a given curriculum. This agenda cannot be fulfilled without teacher mediation that prevents students from going astray and wandering in futile paths and that keeps their modeling activities aligned as closely as possible with scientific inquiry.

Teacher mediation is meant to constantly induce students to reflect back on whatever epistemic or cognitive knowledge that they might already possess and that relates to what they are learning in the classroom. Such reflection is made *insightful* in the sense that individual students become consciously aware of the limitations of their own conceptions and habits of mind, and of the sources of error when committed, and they explicitly realize what makes scientific realism superior to naive realism from all perspectives. The reflection is also *regulatory* in the sense that individual students resolve any incommensurability between their own paradigms and scientific paradigms, and they proceed through a paradigmatic evolution that meaningfully tames down naive realism in favor of scientific realism.

Educational research has systematically shown in the last three decades that student naive paradigms are often reminiscent of pre-Galilean paradigms. Teachers are subsequently encouraged to turn to the history of science in order to better understand the foundations of student paradigms and identify historical cases that may be deployed in educational settings for regulating students' knowledge and resolving incommensurability between student paradigms and scientific paradigms. In this respect, student regulation may be directed in ways that recapitulate the history of science, especially at critical turning points whereby Galileo and his successors relied on systematic modeling of physical patterns to overcome the limitations of naive thinking and take science into major paradigmatic shifts. In fact, student realism is often successfully regulated under modeling instruction to reach certain level of commensurability with scientific realism, by guiding students through processes similar to those of successive refinements of model-laden theory and inquiry which Galileo and his successors went through.

Depending on the level of incommensurability between student paradigms and a given scientific paradigm, and/or the degree of novelty of the latter paradigm (since not every scientific paradigm has necessarily counterpart student paradigms), the intricacy of teacher mediation may go anywhere from providing simple hints to resolve minor inconsistencies, to "lecturing" about a new conception that has no naive counterpart in students' epistemic repertoire. A trade-off exists between student autonomy and teacher authority in mediated learning. The more students are incapable of regulating their knowledge on their own, the more authority the teacher needs to assume, and the less autonomy students may be afforded, in order to ensure that the target paradigmatic evolution takes place efficiently and within the practical constraints of the course. Teachers can anticipate the type of mediation and level of feedback when they are aware ahead of time of the kind of conceptions students possess about the topic of instruction. To this end, modeling theory comes with a battery of diagnostic instruments (available at www.halloun.net), and with means to develop such instruments that would help teachers identify and categorize student preinstructional knowledge state, and subsequently decide what mediation strategy is appropriate.

Student regulation and thus teacher mediation are not only about the target scientific knowledge. They are also about student learning styles and all meta-cognitive factors that underlie such styles. Teacher mediation is thus also about helping students learn how to learn, i.e., helping them develop appropriate learning habits. Special attention is then paid to attitudes toward science and science education, teacher–student, and student–student relationship, confidence, perseverance, and other underlying dispositions. Above all, teacher mediation is conducted so as to help students give up rote learning to satisfy curriculum requirements, and move toward meaningful learning of course materials to regulate their own paradigms. Students are especially directed to take advantage in their everyday life of what they learn in science courses and how they go about learning course materials, and to realize that scientific paradigms, especially scientific habits of mind are viable not only for the development of scientific theory but, most importantly, for any person to conduct oneself in modern life in constructive and productive ways.

Profile Shaping Education

Research was conducted in the last 4 years to extrapolate the work described above into various educational fields outside the realm of science. A novel educational framework emerged as a consequence that calls for education at any level to empower individual students to develop a particular *profile* that helps them succeed in modern life. The profile may be defined in accordance with the local vision for education and adopted metaphysical, cognitive, and educational tenets, and in fulfillment of a number of social, cultural, economic, and higher education requirements. The profile can then be *shaped* or reified in a given curriculum in the form of measurable outcomes that are determined in terms of (a) the paradigm(s) of the field(s) or discipline(s) which the curriculum is about, and (b) corroborated pedagogical principles (or general educational standards) and rules (or operational standards), all grounded in the aforementioned tenets. The nature and repertoire of outcomes are also affected by, and affect, the nature of the existing educational system as well as teacher profile and professional development. Appropriate programs of study, and corresponding methods and means can subsequently be devised to reify outcomes in formal learning and instruction and ascertain the extent to which outcomes are actually being reified in individual students' profiles (Fig. 4.2).

The Profile Shaping Education (PSE) framework offers a particular 4-p profile as an archetype for secondary school and college curricula. The profile in question is that of a paradigmatic, productive, proactive, and principled citizen (Fig. 4.3). Each one of the four p-traits can be translated into appropriate outcomes in a given curriculum in the manner just outlined. PSE provides, for spelling out outcomes, a particular *profiling schema* that has emerged from the modeling schemata in the manner discussed below. Like in the case of modeling theory, PSE calls (a) for any profile and corresponding outcomes to bring into perspective the *paradigmatic* nature of the field(s) which the curriculum is about, and especially the cross-disciplinary nature of habits of mind and generic conceptions, and (b) for outcomes to be *middle-out* structured in accordance with *critical thresholds* similar to those of modeling theory. In further alignment with the modeling approach, PSE calls on instructors to engage students in well-structured *experiential learning cycles* and *mediate* insightful *regulation* of individual students' profiles so that they become *commensurable* with the target student profile.

The Profiling Schema

Profile Shaping Education (PSE) maintains that the main objective of any curriculum is to reify a particular student profile in the form of outcomes that are commensurate with the professional paradigm(s) covered by the curriculum and

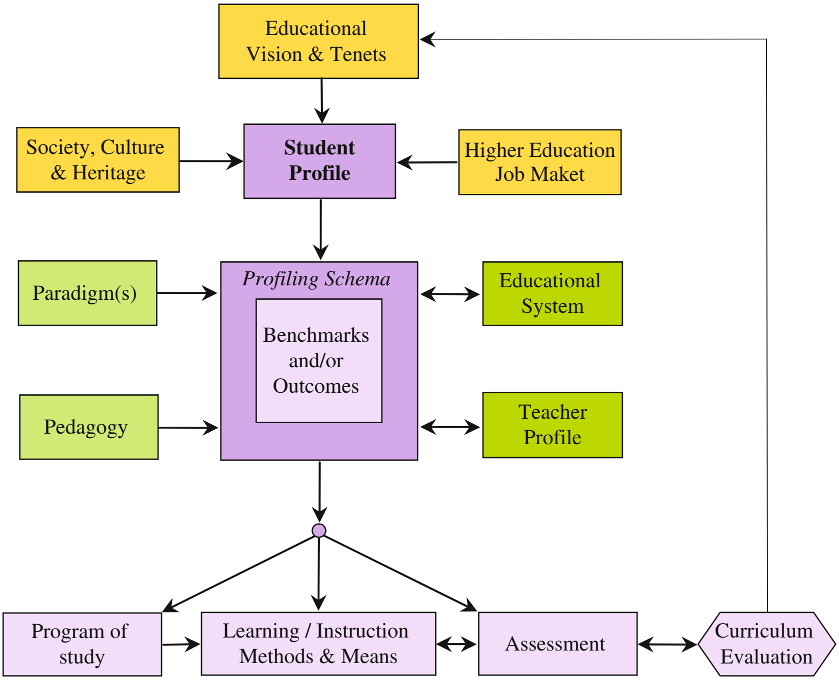

Fig. 4.2 Profile Shaping Education (PSE) curriculum framework

Paradigmatic
A paradigmatic student realizes that knowledge construction and deployment in every profession are governed by certain paradigm(s) in line with which s/he needs to develop her/his own profile. For efficient transcendence of personal paradigm(s), the student concentrates on a balanced and comprehensive repertoire of foundational and generic episteme and cross-disciplinary habits of mind that allow her/him to realize the big picture within and across disciplines.

Productive
A productive student relies on systematic ways and means, cognitive and technical, for meaningful development and constructive deployment of conceptions and habits of mind within each discipline, and for productive and creative extrapolation of conceptions and habits into other disciplines and everyday life.

Proactive
A proactive student adopts a clear vision of her/his education and future, and develops an affinity for detecting and resolving problems and for anticipating, and coping with new challenges. The student continuously seeks, and assumes control of, new learning experiences in order to evaluate and regulate her/his own profile; s/he constructively engages with others to help them do the same, and subsequently to empower self and others for lifelong learning and continuous profile development.

Principled
A principled student embraces positive dispositions, especially those that characterize her/his own culture and disciplinary paradigms, and interacts conscientiously, respectfully and constructively with others and the environment.

Fig. 4.3 The 4-p student profile

that take into account the cognitive potentials of target students. Curriculum designers have then to spell out an appropriate *taxonomy of measurable epistemic and cognitive outcomes* (i.e., conceptions and habits of mind) for the covered fields or disciplines so that the program of study can be devised accordingly, along with appropriate methods and means of learning, instruction, and assessment.

The target student profile is normally defined for a particular school cycle or grade level and not for a particular discipline or curriculum, and so as to concentrate, to the extent that is possible, on generic conceptions and habits of mind that cut across various disciplines and that bring into perspective the big paradigmatic picture within and across disciplines. PSE thus calls for epistemic and cognitive outcomes to be spelled out coherently within a given curriculum, and consistently across various curricula. To this end, it puts at the disposal of curriculum designers, authors and teachers a generic tool which can be used for setting, implementing, and assessing the desired taxonomy of outcomes. This tool is the profiling schema.

The *profiling schema* emerged from, and supersedes, modeling schemata. The new schema is an upgrade of its predecessors in two respects, while it preserves significant aspects of the original schemata. First, one particular modeling schema was originally designed for a particular type of conceptions, mainly concepts and models. In contrast, the profiling schema is a generic tool that can be used for spelling out the outcomes associated with any physical or abstract system, and thus with any type of conception. The new schema is underlined by the main metaphysical tenet of modeling theory which asserts that the paradigmatic realm of scientists or any other community of professionals (just like the physical world) consists of coherent conceptual systems, the make-up of which follows specific patterns, and the construction and deployment of which require generic habits of mind. Second, a modeling schema concentrated on epistemic aspects of a given type of conception. Cognitive aspects (habits of mind) were often dealt with outside the context of modeling schemata in modeling theory, and the focus there was on processes required for model construction and deployment. In contrast, the new profiling schema accounts intrinsically for both epistemic and cognitive aspects associated with any system. Like modeling schemata, the profiling schema focuses on features of any system which research, especially modeling research, shows to be comprehensive, from both paradigmatic and pedagogic perspectives, and critical for students at any level to meaningfully understand the system. Those features mainly belong to two dimensions, the scope and structure of any system.

The *scope* dimension specifies the *domain* of a system (what pattern the system represents in either the physical world or conceptual realm) and its *function* (what the system is good for, and under what conditions). The *structure* dimension specifies the *composition* of the system (what primary entities the system consists of, and what are their salient properties), its *internal structure* (how these elements and their properties are related to each other within the system), and its *external structure* (how the system relates to its environment and/or other systems within and outside the confinement of its paradigm).

Figure 4.4 shows the profiling schema in the form of a template that may be gradually deployed to set the epistemic and cognitive outcomes associated with any system in any educational field, and not only in science. Conceptions and habits of mind may first be stated in general terms (benchmarks) for a given system. As such, the schema serves as a “broad profiling schema”, or “benchmark schema”. Subsequently, or concurrently, conceptions and habits of mind may be translated into measurable outcomes that are suitable for the target population of students. The schema then serves as "outcome schema".

Figure 4.4 illustrates the use of the schema as a benchmark schema in five educational fields in order to show how generic the schema is, and thus how the tools of modeling theory were efficiently extrapolated across various curricula in the context of PSE. The fields in question are respectively physical sciences, mathematics, earth sciences (and geography), and English language. Each cell in the four instances of the benchmark schema is partially filled with certain, but not all, conceptions or habits of mind that are required in typical systems covered at the secondary school or college level (Fig. 4.4). The reader can easily realize that *epistemic* cells include particular information or theoretical statements about the scope or structure of a given system that are commonly accepted by the concerned community of professionals (scientists, mathematicians, or linguists, in the case of our example) and that the student is expected to *have* at a given point of instruction. In contrast, the reader can readily realize that *cognitive* cells include what the student is expected to *be* capable of doing at that stage, and this in the form of habits of mind, processes, or dispositions, which the student

System: Bohr's Atomic Model		**Conceptions**	**Habits of Mind**
Scope	Domain	Hydrogen atom and hydrogen-like (or hydrogenic) ions.	Criterial reasoning and discriminative analysis whereby: (a) a pattern is defined among hydrogenic atom/ions that may be classified together and distinguished from many-electrons atoms or ions, and (b) the appropriate theory is chosen to construct and deploy the Bohr model (e.g., the classical theory governing the so-called standard model).
	Function	Description and explanation of certain, but not other, aspects of a single electron bound on a circular orbit.	Logical and critical reasoning by virtue of which particular questions are specified that the Bohr model may answer, to certain limits, about hydrogenic atom/ions, in the context of the chosen theory. Exploratory analysis to set what the model can specifically describe and explain about hydrogenic atom/ions.
Structure	Composition	A nucleus with one (hydrogen) proton or more (hydrogenic ions), and a single electron. Properties of interest include mass and charge of these entities, and state properties of the electron (e.g. velocity).	Discriminative analysis by means of which specific (primary) entities (electron and nucleus) and object and state properties are exclusively included in the model, and other (secondary) entities and properties are left out.
	Internal Structure	Interaction between the nucleus and the electron partially represented by a central (binding) Coulomb force exerted by the proton(s) in the nucleus on the electron.	Criterial reasoning to establish either structure, say in the context of classical theory, by analogy to planetary models (e.g., Earth-Moon system in the solar system). Relational reasoning to establish relations between primary properties of various entities in the form of state, interaction and causal laws; and representation dexterity to express those laws algebraically, graphically…
	External Structure	Interaction between the atom in question and other neighboring atoms (molecular structure), or other types of environment (e.g., electromagnetic field).	

Fig. 4.4 The profiling schema deployed to set sample benchmarks for specific systems in typical educational fields. (**a**) Sample benchmarks associated with Bohr's atomic model in physical sciences. (**b**) Sample benchmarks associated with the quadratic function (or other power functions) in mathematics. (**c**) Sample benchmarks associated with the greenhouse model/effect in earth science and geography. (**d**) Sample benchmarks associated with narrative texts in English

System: Quadratic Function		Conceptions	Habits of Mind
Scope	Domain	An association or a co-variation pattern between an independent variable (argument) and a dependent variable (function value), whereby for every admissible value of the independent variable corresponds only one value of the dependent variable that is proportional to the second power of the value of the independent variable.	Discriminative analysis, along with criterial reasoning, allowing the distinction between functions and other relationships, and the classification of certain functions as quadratic.
	Function	In mathematics, associating two changing objects, or specifying processes that transform one object into another, such that the value of one is proportional to the second power of the other. In science, describing or explaining the state or change of state of a system whereby a given descriptor relates to another proportionally, and to the second power.	Logical and critical reasoning by virtue of which particular questions are specified that the quadratic function may answer, to certain limits, about certain co-variation between two variables and/or the state of certain physical systems. Exploratory analysis to set what the function can specifically tell about the co-variation in question, or describe or explain about the state in question.
Structure	Composition	One independent variable or descriptor of specific admissible values (argument, x), one dependent variable or descriptor (function, y), and constant coefficient(s).	Discriminative analysis by means of which specific entities (variables and coefficients) are identified, and others excluded (e.g., non-admissible values of x, variable coefficients).
	Internal Structure	The general algebraic form relating various components is: $y = ax^2 + bx + c$. Graphically, parabola depict quadratic functions. Co-variation between the two variables x and y is further specified with the first and second derivatives (rate of change) of y relative to x.	Relational reasoning to establish the functional relationship between the two variables, along with exploratory analysis to extrapolate to derivatives and integrals. Logical reasoning to infer certain conclusions from symmetry, derivatives, tangents, concavity, etc. Communication dexterity to properly depict various aspects of the function with tables, equations, graphs, and other mathematical representations, and objectively and precisely interpret such depictions.
	External Structure	The factor theorem, and integration and derivation of the function relate it to functions of different power order. In science, this results in certain transformations or in new concepts describing certain rates of change or explaining conservation or change of states.	

System: Greenhouse Model/ Effect (GHE)		Conceptions	Habits of Mind
Scope	Domain	Atmosphere of earth, or any similar planet affected by global warming.	Descriptive analysis of the Earth atmosphere and of electromagnetic radiation.
	Function	Description and explanation of global warming.	Logical and critical reasoning by virtue of which particular questions are specified that the Greenhouse Model may answer, to certain limits, about global warming. Exploratory analysis to set what the model can specifically describe and explain about global warming.
Structure	Composition	Terrestrial globe, infrared radiation, naturally occurring gases in the atmosphere (water vapor, CO2, methane, nitrous oxide & ozone), and human-caused gases (hydrofuoro-carbons, perfluorocarbons, sulfur hexafluoride or SF6).	Criterial reasoning to classify and quantify various gases and radiations. Discriminative analysis by means of which specific (primary) entities (gases in the atmosphere and infrared radiation) and object and state properties are exclusively included in the model, and other (secondary) entities and properties are left out.
	Internal Structure	Laws of "optics" describing how infrared "light" can be confined to the Earth atmosphere, and explaining how changes in the atmosphere gases can increase the confinement rate and cause GHE.	Criterial reasoning to establish either structure by analogy to greenhouses used for farming purposes. Criterial reasoning, relational reasoning and inferential analysis to quantify various greenhouse processes and statistically analyze their impact on life on Earth. Communication dexterity to take advantage of various mathematical (including statistical) representations in this respect. Relational and logical reasoning to realize the interaction between human life and atmospheric changes, and appreciate the need to constructively enhance that interaction.
	External Structure	Effect of human activities on earth's atmosphere, and contribution to GHE (e.g., population growth, farming practices, burning fossil fuels, industrial gases, deforestation). Impact of GHE on life on Earth. Necessary changes in people practices, and human adaptation to climate change.	

Fig. 4.4 (continued)

System: Narrative Texts		**Conceptions**	**Habits of Mind**
Scope	Domain	Fiction or non-fiction stories with specific features and generic structure that present a sequence of events according to a specific pattern.	Criterial reasoning and discriminative analysis to classify various forms of texts.
	Function	Description of a plot in which characters are involved in a conflict, and which evolves in a sequence of events starting with the exposition of the conflict, and ending with its resolution.	Logical and critical reasoning by virtue of which particular questions are specified that narrative texts may answer about certain stories and plots.
Structure	Composition	A plot; major /minor characters; characterization; setting; theme; symbols; point of view.	Discriminative analysis by means of which specific (primary) entities and properties are exclusively included in the text, and other (secondary) entities and properties are left out.
	Internal Structure	Specification of various components and description of the way they interact and evolve in a sequence of events starting with exposition, rising action, climax, falling action, and resolution.	Criterial reasoning to ascertain, compare, classify, and contrast to the extent that is necessary characters and settings. Relational reasoning to relate characters and settings, and thus specify symbols, characterization and theme. Exploratory and inferential analysis to describe and explain the conflict, and infer a particular ending. Logical reasoning to set particular assumptions, make metaphors and arguments, and come up with viable points of view, judgments and extrapolations. Communication dexterity to express all the above with clarity and readily allow sense making and objective interpretation of text
	External Structure	Relation to other forms of texts such as expository texts and argumentative texts.	

Fig. 4.4 (continued)

is expected to develop in the context of a given system, but which are of generic nature, in the sense that the student can deploy them in the context of any other system.

Cognitive Taxonomy

Cognitive outcomes or habits of mind which PSE focuses on to help students develop profiles like the 4-p profile described above (Fig. 4.3) include a blend of processes and dispositions that may be classified in a seven-category taxonomy. The seven categories are listed below along with some of the corresponding habits of mind.

Analysis, which includes exploratory processes allowing the description or explanation (cause identification) of the state or change of state of a given system (or phenomenon) and inferential processes allowing, among others, the prediction (or post-diction) of the state of the system under certain conditions. In all these respects, analysis may be either exhaustive or discriminative. Discriminative analysis is conducted to tease out primary or salient features (entities and their properties) from secondary or irrelevant features, whereas exhaustive analysis results in identifying all features without any distinction.

Criterial reasoning, which includes all sorts of criteria-based judgment and evaluation, like comparison, contrast, classification, analogical reasoning, and pattern recognition, as well as estimation and measurement, all done with special attention to reliability, consistency, objectivity, and precision.

Relational reasoning, which includes processes establishing viable (valid and reliable, coherent and consistent) relationships between different features, including syntactical connections, internal or cohesive structure of a system (connecting its features) or its external structure (connecting the system to its environment), correlation, functional relation, synthesis, extrapolation, and transfer.

Critical reasoning, which includes processes of reflective thinking, evaluation of claims and evidence, corroboration of claims and hypotheses, question formulation, problem detection and formulation, challenge anticipation, skepticism, and questioning "facts", all done with special attention to objectivity and precision.

Logical reasoning, which includes processes of evidence-based argument and corroboration, justification, proof, hypothesis formulation, assumptions making, conjecturing, adduction, induction, deduction, generalization, metaphorical reasoning, esthetical reasoning, and insight.

Technical dexterity, which is about efficient and constructive use of computers, ICT media, and all sorts of technical devices that are particularly important in education.

Representation dexterity and communication fluency, which include verbal and symbolic expression, graphic and geometric depiction, kinesthetic expression, coordination of various expressions and depictions, semantic processes of interpretation and sense making, all done with eloquence, clarity, objectivity, and precision.

It is important to note at this point that there is no particular cognitive hierarchy among the various categories. However, a certain hierarchy may be identified within each category that depends on the variation of complexity of, and cognitive demands imposed by, each habit of mind within a given category. For example, within the category of analysis, we may distinguish between exploratory analysis and inferential analysis. Exploratory analysis is about describing or explaining a particular state of a given system, as it exists at given point of space and time. Inferential analysis is about making inferences about the system in question beyond that particular state, e.g., predicting how the system may evolve in the future under certain conditions, or post-dicting how the system evolved in the past before it got to the state in question. One can readily realize that inferential analysis comes at a higher cognitive level than exploratory analysis and that explanatory analysis (identifying salient causes of the conservation or change of state of a system) comes at a higher level than descriptive analysis (identifying primary features of a given state).

A particular cognitive hierarchy is defined in PSE that relates to the gradual construction and deployment of a given system along the dimensions defined in the profiling schema (Fig. 4.4). Accordingly, any person may progressively "know" (or "learn" about) a given system, and develop and deploy any conception or habit of mind, in four consecutive stages. These are in order:

1. *Initiation* (*primitive learning*), when a learner is simply aware that the system exists, but knows nothing or a little about its scope and structure, and is still

incapable of successfully deploying related conceptions and habits of mind in any situation.

2. *Gestation* (*rote learning*), when the learner develops partial knowledge about the scope and structure of the system, and is capable of deploying certain related conceptions and habits of mind, exclusively in the context of the system in question when encountered in familiar situations.
3. *Replication* (*reproductive learning*), when the learner develops satisfactory knowledge about the scope and structure of the system, and is capable of deploying related conceptions and habits of mind, exclusively in the context of the system in question when encountered in familiar situations and new, but mostly similar, situations.
4. *Innovation* (*productive or meaningful learning*), when the learner develops comprehensive knowledge about the scope and structure of the system, and is capable of creatively deploying this knowledge, especially corresponding habits of mind, within the context of the same and other systems encountered in novel, unfamiliar situations.

It is also important to note here that the habits of mind distinguished above are normally gradually developed and deployed not individually but together in various combinations that may be classified in three categories: core-engagement, eco-engagement, and meta-engagement.

Core-engagement, which puts together processes and dispositions from the above taxonomy of habits of mind, in the purpose of looking at the big picture of things within a given field, and designing and carrying out appropriate plans for systemic and system-based thinking (modeling included), problem solving and experimenting with, and regulating (controlling or changing) existing situations in that field. Ultimately, one will bring about creative and innovative ideas and products about the field, at school or in the workplace, as well as in everyday life.

Eco-engagement, which includes self-management as well as interaction with others, especially peers (teamwork included), and the environment, decision making, and crisis management, all done with integrity, fairness, tolerance, empathy, respect of diversity, open mindedness, while upholding commitment, dedication, perseverance, curiosity, adaptability, and assuming responsibility, accountability, and leadership.

Meta-engagement, which includes auditory, visual, and/or kinesthetic assimilation and adaptation of conceptions, and various conscious actions for the development of habits of mind, as well as various meta-cognitive controls that govern learning and, especially, learning how to learn.

Deployment

The profiling schema can be used for spelling out, at any educational level, benchmarks and outcomes associated with any profile, and not just student profiles, as well as for many other purposes. In fact, the schema is currently being used at

ERC to construct electronic assessment and learning platforms, and to help designing and deploying various curricula, including those for preservice and in-service teachers. It is also being promoted for tracking the evolution of every learner's profile, so that appropriate learning activities may be designed that help individual learners efficiently develop the target profile, and so as to ascertain whether a given curriculum actually contributes to the development of the profile in question. Like modeling schemata in science education, the profiling schema has begun to prove itself as a significant factor in enhancing the state of things in any educational field.

Our research had long shown that modeling schemata are most critical for the success of the modeling approach (Halloun, 1994, 1996, 1998a, 2003). Cognitive and educational researchers have long argued and shown that scientists are more efficient than ordinary people, including high school and college students, because to a large extent of better knowledge organization as reflected in scientific theory and paradigm. Modeling schemata serve, for both teacher and student, as a tool for epistemic organization. When students are explicitly directed to construct (and deploy) scientific conceptions, especially models, in accordance with these schemata, their understanding of course materials as reflected in course exams and standardized testing reaches significantly higher levels than their peers, including those who follow a modeling approach that does not rely on such schemata (Halloun, 1994, 1996, 1998a, 2003).

Research has begun about 2 years ago on the effectiveness of the profiling schema in various ERC projects. The schema has proven to be instrumental especially in the development of the International Arab Baccalaureate (IAB). IAB is meant to be a common secondary school diploma for the entire Arab World that will, in due course, be internationally recognized. Students are expected to receive the IAB diploma if they develop the profile shown in Fig. 4.3, evidence for which is ascertained through continuous formative and summative assessment of expected outcomes in various fields covered in the three secondary school grades (10, 11, 12). In preparation for its official launch in the academic year (2010–2011), IAB has been piloted twice so far, once in May 2009, and another time in March 2010. The first pilot took place in the form of a comprehensive summative exam for grade 12 students in four Arab countries, and the second pilot took place similarly in grades 10, 11 and 12 in the same countries. The first pilot covered physics, mathematics, and Arabic language, whereas the second pilot covered physics, chemistry, biology, mathematics, geography, Arabic, and a foreign language (English or French). Pilot exams covered outcomes in the mentioned fields that pertain to the profile of Fig. 4.3 and that were determined using the profiling schema illustrated in Fig. 4.4.

A major focus of both pilots was to find out to what extent PSE provides a valid and reliable cross-disciplinary framework for ascertaining the extent to which students develop the target profile (and for ultimately developing the profile). Among others, this meant to ascertain to what extent the profiling schema can be relied upon to set profile-based outcomes for various targeted fields at various grade levels. Last year's data showed that the profiling schema has actually served its purpose in significant ways. For instance, Pearson correlation coefficient among the three exams then administered in grade 12 ranged from 0.51 ($p = 10^{-20}$), between Arabic and mathematics, to 0.59 ($p = 10^{-31}$), between mathematics and physics. Closer data analysis revealed that common epistemic and cognitive outcomes laid out in the profiling schema were responsible to a large extent for such high correlation. Data of this year's pilot are still being analyzed, and results will eventually be made available at www.EducationalRC.org/IAB

Acknowledgment The author would like to extend his gratitude to all those who made this work possible, especially colleagues at Educational Research Center and elsewhere involved in the development of PSE and IAB, and students, teachers, and administrators at the schools that participated in the IAB pilots.

The work reported in this chapter was carried out, in part, under the auspices of Educational Research Center (ERC) in Lebanon. Views expressed in this chapter are solely those of the author, and do not necessarily reflect the position of ERC.

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Part II
Modeling and Student Learning in Science Education

Chapter 5
Helping Students Construct Robust Conceptual Models

Colleen Megowan-Romanowicz

Modeling Instruction has been practiced in science and mathematics classrooms across the United States and around the world for over 25 years. Force Concept Inventory (FCI) scores from over 30,000 students confirm that this approach is one of the most successful science education reforms in the last 50 years. Modeling Instruction arranges the subject area under study into a handful of basic conceptual models. Students working together in groups of three or four uncover, construct, test, and apply these models as they engage in carefully chosen laboratory activities followed by model exploration and deployment exercises. Written work is carried out on student whiteboards, with problem representations and solutions collaboratively constructed and then shared and interpreted in discussion with the entire class. Managing the classroom discourse around these whiteboarded representations to leverage the construction of coherent, useful conceptual models requires skill on the part of the teacher. This chapter will explore what teachers can do to optimize the way students use inscriptions and discourse to construct conceptual models for use in physics and mathematics.

A Brief History of Modeling Instruction

In 1983 high school physics teacher Malcolm Wells, a graduate student under the direction of David Hestenes, tested his students using Halloun and Hestenes' *Mechanics Diagnostic*. Results of Halloun's research utilizing this test revealed that student misconceptions about force are surprisingly robust and persist beyond instruction regardless of the teaching method or the instructor's qualifications (Halloun & Hestenes, 1985). Wells, by all accounts an excellent teacher who had already adopted a student-centered inquiry approach based on learning cycles (Lawson, 1986, 1994, 2010), was shocked at how poorly his students did post-instruction on this simple measure of student beliefs.

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_5,

After interviewing his students to explore the nature and extent of their misconceptions, Wells redesigned the mechanics portion of his physics course, organizing the content around a handful of conceptual models as described by Hestenes (1979), (1987). Adding his newly acquired understanding of the structure of models and the stages that characterized the activity of modeling to his existing instructional design of learning cycles, Wells developed what he called a Modeling Cycle which had two distinct stages: (1) *model development*, consisting of description, formulation, ramification, and validation, and (2) *model deployment,* in which the model developed in stage 1 is applied to a variety of novel physical situations (Wells, Hestenes, & Swackhamer, 1995).

The results of this model-centered collaborative inquiry approach were dramatic. Students' posttest scores on the mechanics diagnostics increased by a standard deviation or more. Based on these findings, Hestenes and Wells collaborated on the preparation of an NSF grant to develop and disseminate this new approach to physics instruction. In its first funding cycle, NSF-funded Modeling Workshops trained teachers and developed a mechanics curriculum anchored by a suite of paradigm labs that were used to introduce each of the models.

Subsequent NSF funding has allowed the Modeling Instruction program to conduct nationwide teacher workshops in physics, chemistry, and physical science with mathematics; develop second semester curriculum materials and workshops for light, electricity and magnetism, mechanical waves, a full-year 8th/9th grade physical science with mathematics modeling course, and a full-year chemistry modeling course. NSF funding has also supported the creation of a Master of Natural Science (MNS) degree program for high school physics teachers at Arizona State University featuring integrated physics and chemistry, integrated mathematics and physics, physics and astronomy, astrophysics, energy and the environment, and several contemporary physics offerings—spacetime physics, light and electron optics, matter and light, and structure of matter—in addition to the full suite of Modeling Workshops mentioned above. All courses are centered on conceptual models and scaffold learning with the use of Modeling Cycles. In late 2009, the NSF granted funding to develop a Science, Technology, Engineering, and Mathematics (STEM) Modeling MNS degree program for K-8-certified teachers to prepare them to teach science and mathematics in middle school.

Malcolm Wells passed away in late 1994 but his innovative approach to teaching and learning lives on. A 2007 survey found that 9% of US physics teachers utilize Modeling Instruction (Neuschatz, McFarling, & White, 2008).

The *Force Concept Inventory* (FCI), a refinement of the *Mechanics Diagnostic* that was used to measure student gains in Wells' research in the early 1980s (Hestenes, Wells, & Swackhamer, 1992), continues to document robust conceptual gains by students in classrooms where Modeling Instruction is practiced. A 1998 study of over 6,000 students by Richard Hake showed gains for students in classroom utilizing interactive engagement methods (such as modeling) of up to two standard deviations over those of students in classrooms where the more traditional lecture-demonstration format prevailed (Hake, 1998).

Modeling Workshops have been offered in 41 states over the past 18 years. Over 3,000 teachers have taken one or more Modeling Workshops. Modeling teachers can be found in 48 of the 50 states as well as Europe, Japan, Singapore, and Australia. The horizontal propagation of this reform teaching method from teacher to teacher and school to school has not profited from the commercialization of modeling curriculum materials, which continue to be made available free to every teacher who takes a workshop. Indeed the lack of a modeling text has hindered its adoption by numerous school districts whose teachers identify themselves as modelers. Districts and states typically require the adoption and purchase of a textbook with content aligned to state standards in spite of the fact that research has shown that text-based physics courses produce students who are less capable than those who learn physics without a text (Sadler & Tai, 2001).

The Modeling Classroom

Culture

One of the key elements of the Modeling Method of Instruction is the notion that the routine social and socio-scientific norms of the classroom can and should be rewritten. Modeling Instruction relies heavily on student-centered collaborative learning. This is accomplished via the engagement of small groups, typically three or four students, in a series of tasks whose structure reflects the structure of the conceptual model under investigation. Students work together to identify, explore, and elaborate fundamental physical relationships—models—and then generalize these relationships for use in solving novel problems with similar structure. They present and defend their findings to their classmates via whiteboarded presentations that involve multiple modes of representation of the data they have collected and interpreted (see photo). Central features of the culture of a modeling physics classroom are inquiry, observation, collaboration, communication, and reasoning.

Whiteboards are an important cognitive and communication tool—a place for students to represent what they have discovered or negotiated in collaboration with their peers—the processed data that map a problem space as they have come to understand it and illustrate their assertions (Megowan, 2007) (Fig. 5.1).

While success in a modeling classroom is typically measured in the conventional way—by the accumulation of points—these points are, ideally, earned by interacting with peers to successfully construct, validate, and apply conceptual models rather than for simply rendering correct answers.

Most students do not enter into such a learning environment with the skills to participate productively. Years of conditioning to the conventional culture of schooling in which they are immersed from age 5 lead the majority of students to believe that in order to get ahead they must sit still, be quiet, listen to the teacher, follow directions, fill in the blank, wait their turn, raise their hand, finish in the allotted time, and, above all, get the right answer. The teacher sets the agenda and calls the shots,

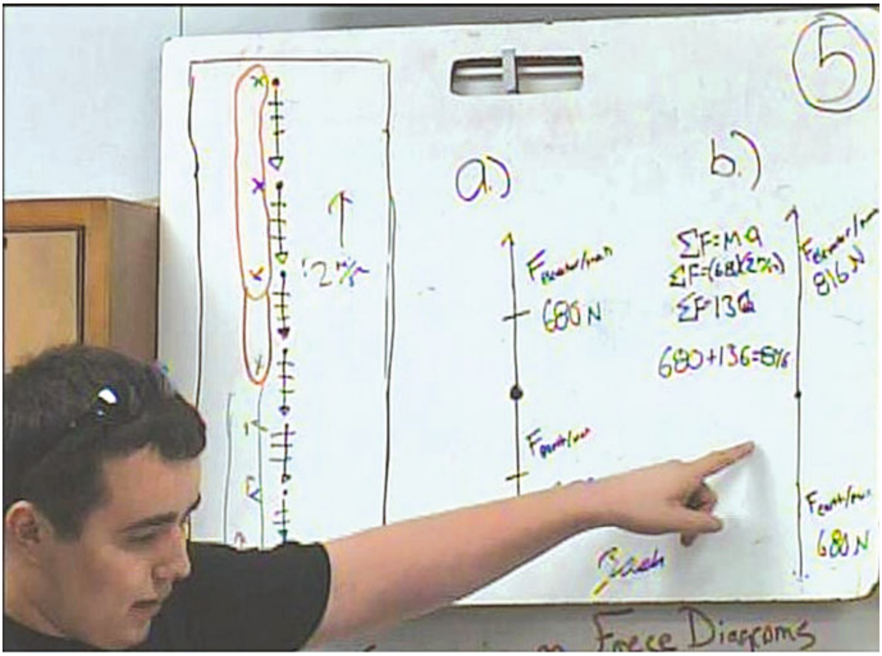

Fig. 5.1 A student leading the discussion of a whiteboarded problem

and the ultimate goal for students who wish to succeed is to *get the teacher to give them points*.

A new classroom culture must be brought about in order for Modeling Instruction to succeed, and to do this both teacher and students must be clear about what is expected and *what works*—what advances thinking and learning in this environment. Teacher questioning must be open ended and teachers must learn to wait through those inevitable awkward silences rather than rushing to call on someone else or simply supplying the answer themselves so that the discussion can move ahead. Rather than passing judgment on whether it is right or wrong, teachers must accept every answer as a potential window on student thinking—a snapshot of a student's conceptual model as it is being built (or dismantled and rebuilt as the case may be). Teachers and students alike must value and press each other for sense making and for answers to be justified. In short, the typical hierarchy of the classroom must evolve to a more horizontally integrated learning community where students feel that they can look with confidence to their peers to help them learn.

Redesigning the learning environment in this fashion is effortful for both teacher and student but with time a rich discourse environment emerges. It is the skill with which the teacher learns to manage this discourse that determines the quality of the conceptual models that students construct, and it is the acquisition and practice of these discourse management skills that is the chief activity of the Modeling Workshops teachers attend in order to learn the practice of Modeling Instruction.

Motivation

For the activity of modeling to take place students must opt to engage in the classroom discourse enterprise. How does Modeling Instruction induce engagement? One key feature of this instructional approach is its emphasis on doing science as scientists do. Students are enculturated into the ways of scientists rather than just taking science classes. Sociolinguist James Gee likens traditional physics instruction to 'reading a manual for a videogame that you will never play' (Gee, 2007). Modeling physics encourages students to play the game of physics before reading the manual.

Students will opt to engage in some learning experience (or not) based on their assessment of its value as 'academic fun,' i.e., their likelihood of success in the context of this activity (Middleton, Lesh, & Heger, 2003; Middleton, 1992). According to Middleton et al., students evaluate academic fun based on the levels of arousal and control that it affords them. Arousal is a function of whether or not an activity is stimulating and/or relevant to their interests or experiences. Control has to do with whether they can choose among multiple opportunities and/or ways to succeed.

One area in which control is a factor in classroom discourse is who 'has the floor' (Edelsky, 1981)—that is, who decides who gets to speak. In traditional didactic classrooms, except for rare instances, the teacher always holds the floor. In modeling classrooms, the students may have control of the floor for extended periods during small group and whole group discourse.

The tasks that students are given in modeling physics afford some measure of both arousal and control. They are embedded in familiar contexts, and the Modeling Cycle that is utilized allows students to continually express, test, and revise their model as they construct it. They play the game of physics as they learn its rules.

Student Thinking

Assuming that students will elect to engage in the learning culture that characterizes their modeling classroom, what might this mean in cognitive terms?

Students do not enter their learning environment as tabula rasa. New learning is overlaid upon a great deal of pre-existing 'organized' knowledge. In designing learning environments it is necessary to consider how existing knowledge is structured and accessed, how new information is assimilated into or coordinated with existing models of the student's world, and how the interactions between students, their tools, and artifacts affect the learning experience.

Learning in a school setting is typically situated in a context and mediated through social interaction, activity, and representation. Cobb (2002) and Doerr and Tripp (1999) have suggested that a classroom community is a legitimate unit of analysis when examining student reasoning, and that in such a setting, content knowledge can be seen as an emergent property of the interactions of student groups. Tools, artifacts, and inscriptions—written representations (Roth & McGinn, 1998)—are observed to be critical components of this relation, as is the social setting in which the interaction takes place.

Cognitive scientist Edwin Hutchins has dubbed this phenomenon ‘distributed cognition’ (Hollan, Hutchins, & Kirsch, 2000; Hutchins, 1995), and his theory of distributed cognition seeks to illuminate the organization of such cognitive systems which include not only groups of people but also resources and materials in their environment.

Hollan et al. (2000) cite four core principles of distributed cognition theory:

- People establish and coordinate different types of structure in their environment.
- It takes effort to maintain coordination.
- People off-load cognitive effort to the environment whenever practical.
- There are improved dynamics of cognitive load balancing available in social organization.

The sense-making that is done by a small group of students as they study a physical system, and negotiate what they will write on a whiteboard to share with their classmates and agree what their inscription means, can be viewed an instance of distributed cognition in the classroom. The social organization of the group forms a cognitive architecture that determines how information flows through the group. Individual members of the group take on different (unassigned) roles as they progress through the task, enabling the team to optimize its performance by exploiting the unique strengths that each member brings to the partnership. Modeling Instruction facilitates and frames this process by structuring the learning environment around a series of activities done by small groups working collaboratively.

The Modeling Experience

The Study

In an attempt to gain insight into the ways in which collaboratively constructed visual representations aid students’ collective sense making, I collected and analyzed four videotaped data sets:

1. a 4-week, twice-weekly participant/observation in a middle school mathematics resource class at an urban K-8 school;
2. a semester-long daily observation in an honors physics class for 11th and 12th graders at a suburban public high school;
3. an 8-week observation in a 9th grade physical science class at a large suburban public high school; and
4. a semester-long observation at a suburban community college in a second semester calculus-based physics course on electricity and magnetism.

These data afford a view of ‘cognition in the wild’ (Hutchins, 1995), providing a detailed account of students’ reasoning and communication practices that are comparable to what other members of the class—both students and teacher—are privy to on a daily basis. This is essentially a work of cognitive ethnography—an event-centered approach that allows one to study the complex interactions among individuals, their tools, and artifacts as they work jointly on complex tasks. The primary cognitive unit for this analysis was the small group—usually three or four students who typically work together to prepare a whiteboard for presentation and class discussion.

Findings

Modeling Activities

Whiteboarding

The discourse of physics is about the physical world and as such is necessarily spatial in nature. In the modeling physics classroom, a whiteboard is used by students working together to create a common picture of the physical situation they are attempting to understand. In a sense, it assigns an 'absolute' reference frame to the situation (Peterson, Nadel, Bloom, & Garrett, 1996), eliminating one potential source of miscommunication among group members and insuring that all elements of the problem space are mutually manifest (Sperber & Wilson, 1986). As students construct whiteboarded representations, the verbs and prepositions they choose as they negotiate these inscriptions with one another can provide the teacher with a window on the metaphors that shape their reasoning processes.

The Architecture of Modeling Discourse

Another source of insight into the distributed cognition that is taking place in the course of whiteboard preparation and sharing is the structure of the discourse itself (Lemke, 1990). Who leads the conversation? Who writes (or erases what is being written) on the whiteboard? What information is deemed worthy of incorporation into the inscriptions being negotiated? When are spatial representations introduced and how are they used (or not) in reasoning about the problem? When the whiteboard is presented to the class after it is complete, what is mentioned and emphasized? What is ignored?

Whiteboards illustrate or at least imply the following:

- How students see the problem space—the elements of the conceptual model that they attend to in the problem space and how well or poorly they are defined
- How they fit together (structure or at least correspondence)
- How the information in the problem space maps onto these elements of their conceptual model
- How they navigate or manipulate their conceptual model to answer the question that the problem poses

The extent to which whiteboards actually show these things is a function of 'the rules of whiteboarding' in an individual classroom. Over time, a set of conventions about what should and should not be included on a whiteboard evolves in every classroom. Here are some common ones:

- A whiteboard must include graphical, mathematical, and diagrammatic representations of the problem.
- A whiteboard must 'show work,' i.e., computations.
- A whiteboard must show 'the answer' to the problem.

Connecting Discourse with Whiteboarded Representations to Make Sense of Student Thinking

What are they paying attention to?

In theory, these appear to be good rules. In practice, they may hide important evidence of how students thought about the problem as they solved it. The most common missing step in the solution process that I observed early in the school year was a tendency to move straight to the algebraic solution pathway without making or even discussing a graphical or geometric representation, and then once the agreed upon 'right answer' was found algebraically, students would go back and construct the required graphical or geometric images that would support the correctness of their solution. The following transcript excerpt from an Honors Physics class early in the semester demonstrates this:

(Zane, Hannah, Gui and Jimmy stand at their lab table waiting for the teacher to walk by and assign them a homework problem from the previous evening's assignment to begin whiteboarding. The teacher walks over to their table.)
TEACHER: Number 6
ZANE and JIMMY: Number 6 (the repeat in unison as they turn their worksheets over in search of the assign problem.)
ZANE, JIMMY and HANNAH: 8.8 (all three students read the answer simultaneously from their worksheets).
GUI: I got 4.4
ZANE: You probably did it wrong. . .here, let's work it out. Let's work it out.
Let's do it on the board.
JIMMY: Start by writing the equation.
ZANE Yeah.
JIMMY: Delta x. . .

Zane carefully copied his algebraic solution on to the whiteboard. Only after this was complete did Hannah point out to him that they were also supposed to have a graph on their whiteboard. He added a small graph as an afterthought. A few minutes later when the group presented their solution to the class, Hannah described each procedural step in manipulating the equation to find a solution. Not once did they mention their graph and no one (not even the teacher) asked them about it.

In some cases, students omitted this step entirely, recording only an algebraic solution on their board. That they did this repeatedly was an indication that the algebraic solution culminating in 'the answer' was 'what counted' for these students.

Whiteboard-Centered Activities

There are three whiteboarding-centered activities that are characteristic of modeling classrooms: laboratory investigations, going over homework problems, and practicing with the model, and each of these entails two phases—small group whiteboard preparation and sharing with the whole class.

When whiteboarding a laboratory investigation a small group of students collects and displays data—usually graphically and diagrammatically—and then represents the relationship between the quantities under investigation algebraically in the form of an equation. Then the entire class gathers into a large circle—called a board meeting—where everyone can see each others' whiteboards, and they discuss and make sense of their findings. This discussion may be teacher led or student driven—the latter being the more effective model for constructing student understanding (Fig. 5.2).

The activity of going over homework involves each student group displaying their solution for one of the homework problems on a whiteboard and is often shared with the whole group in a series of stand-up presentations where small groups come to the front of the classroom and present their solution, after which there is an opportunity for questions from the teacher or the class (Fig. 5.3). In practice, students seldom take advantage of this opportunity, leaving the questioning to the teacher.

Practicing with the model occurs when the teacher poses a problem that all the whiteboard groups are directed to solve. It is typically a fairly open-ended multipart

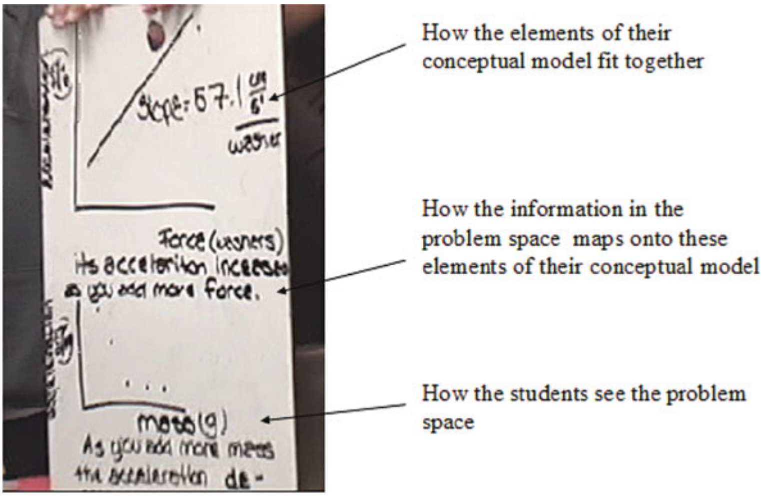

Fig. 5.2 Students grapple with the relationship between force and acceleration

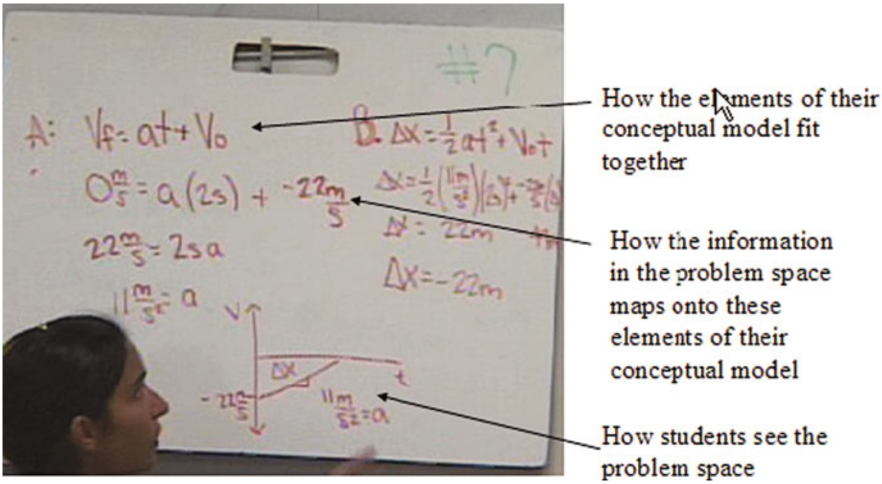

Fig. 5.3 Students consider the motion of an object moving backward and slowing down

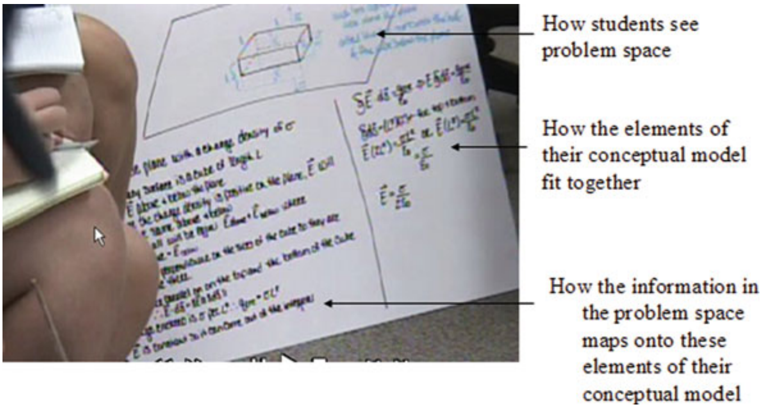

Fig. 5.4 College physics students conceptualize electric field

question that allows for some interpretation. As students work, the teacher moves from group to group, monitoring progress and making an occasional suggestion when a group gets stuck. When whiteboard preparation is complete the students share their solutions in a board meeting as described above (Fig. 5.4).

In all of the whiteboarding activities described above the initial sense-making process takes place within a small group of students. The activity structure differs in these three situations but falls into general categories. In each case there are students who take a proactive role in the conversation and the representing and others who are more reactive or passive participants. Laboratory activities allow for more students to assume active roles simultaneously as students must manipulate an apparatus; make measurements; and record, manipulate, and represent data.

The Power of the Marker and the Power of the Eraser

In the going over homework activity structure, one member of the group whom I will refer to as the decider typically takes the lead and constructs important parts of the whiteboard based on what he/she has previously written on his homework worksheet. Although all group members typically contribute to the conversation surrounding the construction of representations, it is often this decider's version of the solution that is represented. I refer to this phenomenon as the Power of the Marker. In general, although group members might want something to be added to or changed about a solution, the decider retains veto power over what appears on the whiteboard. Controlling the marker essentially amounts to controlling the floor in a small group whiteboard discussion and the decider does this by choosing to either write down or ignore the contributions of others. However, if his version does not sufficiently honor and incorporate input from others, one or more of his teammates may intervene by erasing what the decider has written. This is referred to as the Power of the Eraser. When a teammate asserts the Power of the Eraser, either the decider recreates a more collaborative depiction of his teammates' views or the Power of the Marker is ceded to another group member who will attempt to do so. In this way, all members of the group have an opportunity to see their contribution to the solution represented, although power relations among group members affect the degree to which each person's voice is heard in such a setting.

The Power of the Eraser in small group work is an affordance that is unique to whiteboarding as a platform for sharing small group work with the whole class. When small groups negotiate around representations they construct on chart paper, erasing is not possible and although students are typically assured by the teacher that if they need another sheet they can take one in classrooms that use chart paper, in practice students rarely opt to do so.

By contrast, in both the laboratory activities and the practicing with the model activity structures, members of the group are constructing their understanding of the problem together as the whiteboard is being prepared rather than negotiating what to write down about a problem they have each solved separately beforehand. In these activities, both the marker and the eraser tend to pass from one person to the next often during the construction of a representation as they try out various approaches to the problem. Group members typically contribute to the discourse as co-equals and no one person controls the floor in these conversations. The discussion is less apt to be about whose version of an idea should appear on the whiteboard and more apt to center on what it means to write one thing as opposed to another. There is more erasing and rewriting in these episodes as students jot down diagrams, graphs, or equations to help them communicate their thinking to their teammates or visualize the various elements in a model, how they stand in relation to one another, and how they can be manipulated. This may also be an effort to manage cognitive load (Gerjets & Scheiter, 2003). If they off-load their ideas in the form of written inscriptions, this frees up working memory to handle different information. Another side effect of this practice is that it serves as a 'think-aloud' exercise that allows others to know how the person writing is structuring their conceptual system.

When using the whiteboard in this way, as a medium for communicating partially formed knowledge structures, some students appear to prefer to ‘think aloud’ in spatial representations and others prefer to ‘think aloud’ in algebraic representations. Those whose preferred mode of written communication is algebraic are more often talking to themselves than to other members of the group. This is confirmed by the fact that although they may speak as they write, the talk is seldom directed to anyone in particular, and it is seldom answered by the speaker’s groupmates.

The Role of the Teacher

In general, it appears that distributed cognition across multiple individuals occurs more often when students are practicing with the model than when they are going over homework as the floor and the marker change hands during discourse. It is up to the teacher, then, to provide opportunities for students to engage in this type of thought-revealing activity by designing tasks or problems that are meaningful to students, that permit multiple approaches and solution pathways, and that require students to map the elements and their relationships of a problem onto some conceptual model. The solutions to these tasks must yield some construct that is generalizable for use in other situations (Lesh & Doerr, 2003).

In addition to providing good problems, the teacher can take a peripheral role in the small group whiteboarding activity by circulating in the classroom while students discuss and prepare their whiteboards, listening to conversations and observing what is written on whiteboards and asking an occasional why…?, what about…?, or what if…? question that prompts students to think more deeply about the solution pathway they have chosen. The teacher can also take this opportunity to seed questions or ideas with particular individuals or groups that she hopes will emerge on the board meeting discussion that follows small group whiteboard preparation (Desbien, 2002). And finally, eavesdropping on small group conversations around whiteboards allows a teacher to pick up on patterns of weakness or lack of coherence in students’ conceptual models that she can press on during the board meeting to elicit further thought and discussion.

Critical Factors in Discourse Management—The Board Meeting

While discourse in small groups is largely under the management and control of students, the teacher is the architect of board meeting discourse. In a typical classroom setting students expect the teacher to lead whole group discussions. A good board meeting is one where the teacher prompts the discussion to begin but then pulls back so that the *students assume control*, and this is the behavior that must be learned both by teacher and by students. However, this can be difficult as students are very good at waiting for others to initiate discussion, and generally they appear to prefer to know what they say is right when they contribute to a classroom conversation.

These predispositions present special challenges for teachers who want students to step up and take the lead in helping one another make sense of complex ideas. It is critical that from the beginning of the year, the teacher be explicit about her expectations regarding students' role and participation in board meeting discourse. As quickly as possible, the teacher must withdraw the supportive questioning she typically supplies to keep a discussion moving forward and leave the way open for students to step in and supply one another with the necessary scaffolding.

In order to do this, students must know how to ask good questions. They learn to do this by imitation. If the teacher asks them the same kinds of questions over and over again as she wanders the classroom observing whiteboard preparation, eventually students begin to question one another in the same way. The questions and questioning strategies that teachers 'seed' as they circulate in the classroom and drop in and out of small group whiteboard preparation conversations are echoed by students as they help one another work through problems during board meetings (Desbien, 2002).

This does not happen overnight, however. Some students who are new to modeling are reluctant to participate in this seemingly speculative process. These students can be drawn into the conversation by the teacher asking them whether they agree with some reasoning or interpretation expressed by a classmate or to restate what was said in their own words. If they are unable to do so, the class is charged with restating the explanation in a way that this student understands. Turning the burden of explaining over to students casts them in the role of peer tutor. The goals of board meeting participants shift from 'getting the right answer' to making sure their classmates understand the problem. When the students adopt this goal, they will persist in discussing a complex problem long after the answer has been revealed because they understand that their *real* problem they are expected to solve is how to make the basic underlying structure of the problem—the model—clear to all participants.

One way a teacher can gauge the quality of board meeting discourse is to pay attention to how many student contributions are directed to the teacher. If students are seen by their peers to be speaking to the teacher, they do not actively engage in formulating a reply to their classmate's remark. On the other hand, if students' remarks are perceived as directed toward one another, then every other student is a potential respondent. In fact, if some student participant does not respond, the conversation will stall and an uncomfortable silence will ensue. In order for students to take and hold the floor, then, the teacher must refrain from rescuing them when periodic silences occur in board meeting conversations. Unless the discussion is at an end (which means that members of the group are satisfied that everyone understands the solution to the problem and the underlying conceptual model upon which it is based) the teacher should wait, just as the students are waiting, for some student to get it moving again.

If they have genuinely reached an impasse, students will resort to asking the teacher a question. At this point, the teacher must enter the discourse. To keep from taking control of the conversation, the teacher can reply with a question that redirects students to some element of the conceptual model or some aspect of the problem space that they might find useful in reengaging with the problem. Or, if the teacher thinks, based on the content of the conversation, that one of the students in the group has an important idea that has been overlooked, she might suggest that the group revisit this person's idea. It is important in this case to give students as little prompting as possible to help them restart the discussion and then to once again withdraw to the role of observer leaving the students to control the conversation.

The physical configuration of the students and teacher during a board meeting makes a difference. The ideal board meeting takes place in an open space large enough for students to gather, seated, in a circle so that everyone can see everyone else's whiteboard. When space does not permit this, it is still usually possible to have the students stand in an approximately circular array holding their boards in front of them so that everyone can see them. The teacher should remain outside the circle. If the teacher enters the circle, control of the conversation is immediately ceded to her. In fact, the further away from the circle the teacher positions herself, the better the students will do at keeping the discussion moving forward. I have observed teachers sitting with their back to the group or leaving the room entirely and listening from outside the door in order to promote more student-driven sense making during a board meeting.

At the close of a board meeting it is necessary for someone to summarize what was learned. The teacher must reenter the conversation at this point and will usually prompt this closing summary by asking a member of the group to recap the discussion. However, if she feels there is still some confusion about key ideas she may guide the group to construct a summary by asking a series of questions that help them identify the key elements and how they connect.

Understanding the Conceptual Models Students Construct

It should be evident by now that in order for a teacher to be a good questioner, she must be a good listener. As she moves among the small groups preparing their whiteboards, there are a number of clues available to how students are thinking about a problem. One obvious place to look for clues is in the diagrammatic representation they construct. Is it accurate? Is there anything missing? Are the elements properly identified and relationships properly expressed? Are all members of the group referring to them in the same way? Prepositions are words that express spatial and temporal relationships between elements—important ideas in physics and mathematics. When a teacher hears students connecting the elements of a conceptual model using different prepositions—'to' rather than 'over' or 'from' rather than 'below'—she might find that the students using these alternate ways of describing an event interpret the action described in a problem in a different way. This can be probed with a what if...? question.

Another place to look for clues to thinking is in the coordination of the multiple representations that appear on a whiteboard. Are the graph, the diagram, and the algebraic representations all describing the same thing and does it match the problem statement?

Zooming

Students in both physics and mathematics often take refuge in symbols and symbol manipulation. The initial paradigm lab in which students engage in a Modeling

Instruction sequence typically results in an equation, and instead of viewing this equation as *a mathematical representation that encodes the structure of the model* they are building, they sometimes mistake it for the model itself.

If we take the microscope as a metaphor for the student's way of viewing a problem, it would be as if the student immediately zooms to high power in order to see the fine details of the problem space. Once he has these details in focus, however, he must not forget to zoom back out in order to make sense of the problem by putting what he sees into some sort of 'big picture' physical context. At times, however, students overlook this critical 'zooming out' step, and this is a place where careful probing by the teacher can help them refocus and develop some skill in knowing when and how to zoom in and out.

Jackendoff's Theory of Representational Modularity posits that language does not enter our thoughts directly as a spatial representation (SR) but must pass through the conceptual structure (CS) which encodes propositional representations and then passes them through the CS–SR interface so that they can be interpreted spatially (Jackendoff, 1996). An equation is a propositional representation into which language can be readily transformed. If students choose this route as their preferred solution pathway they sometimes dispense with the task of translating the conceptual structure (CS) that the semantic frame brings along into its corresponding spatial representation (SR).

Zooming out to consider the bigger picture of the problem space—the physical elements and their spatial and temporal relationships to one another— involves crossing what Jackendoff calls the CS–SR interface, a module that affords the mapping of information from conceptual structure to spatial representation and vice versa. This interface module is bidirectional, that is, it allows information to pass from CSs such as languages, heard or spoken, to SRs, which are essentially geometric. Although we learned to think in SRs as infants, long before CSs such as language and mathematical symbol systems were available to us, some students have a preference for encoding information from a problem in a CS which may lack important spatial and temporal information, and unless coaxed, they may not invest the necessary cognitive resources to map the information onto some SR. Likewise there are students who prefer SRs—so-called visual learners who sometimes struggle to translate spatial information into algebraic expressions. The best composition for a small group preparing a whiteboard is to have at least one member from each of these categories.

When a teacher regularly calls upon students to coordinate graphical, mathematical, and diagrammatic representations with one another, she is helping her students learn to zoom in and zoom out—teaching them to move back and forth across the CS–SR interface in order to reframe the problem and build a more coherent conceptual model. This strategy is a cornerstone of effective Modeling Instruction. With practice, students gain confidence in traversing the CS–SR interface, and they will prompt one another to zoom in or out periodically during the problem-solving process, not only just when they reach an impasse but also to verify that their approach makes sense on both levels. Data from my studies show that students who move toward reasoning from SRs as well as CSs are better able to choose appropriate models and apply them to solve problems and to explain their solutions conceptually (not just procedurally) to their peers.

The body of videotaped data I collected revealed that novice modelers in physics did not waste much time thinking about space or time in solving kinematics problems. They extracted the necessary information from each problem, assigned it a symbol, plugged it into the equation they hoped was the right one, performed the appropriate algebraic manipulations, punched buttons on their calculator, and produced an answer that might or might not have some connection to reality. The problem space itself remained largely unexplored. Algebraic formulations were the focal points of their whiteboards and they invoked algebra to justify the answers they produced.

The Role of Spatial Representations (SRs)

With time and consistent effort on the teacher's part to help students learn to construct and coordinate graphical and diagrammatic SRs with the algebraic information they were able to abstract from the problem, students' appreciation of and reliance on SR's grew. This led me to listen carefully to what students talked about, what counted for them as justification for the choices they made, and this gave me some sense of how the SRs they employed functioned to keep them more grounded in the problem space.

Initially, students drew SRs on their whiteboards because they were required to do so. If they did not include the appropriate diagram or graph on their whiteboard, it would be incomplete and therefore incorrect (i.e., it would not receive full credit). *SRs, then, were about following directions.*

Making SRs were also occasionally about demonstrating a skill. Just as a student might have some computational skill that she demonstrated by setting up and solving equations, she might also possess the skill of drawing an accurate, good-looking graph or diagram. *SRs, in this case, were about showing off.*

Occasionally SRs helped students set up a geometric solution to a problem, i.e., determining the area under a curve. Such solutions were dependent on a student's facility with unitization and thus hinted that some measure of spatial or temporal reasoning was an influence on their choice of solution strategy. Generally, however, they were simply used to justify the use of a certain algebraic formulation of the data. At least this approach included the mapping of graphical representations of space or time to algebraic symbols. *SRs, in this instance, were for justifying equations.*

In each of the cases mentioned above, SRs, when they were included, were about getting answers. Moreover, the focus of students' presentations of these whiteboards was the answer they had computed (in particular, the number—units were often overlooked). Students who focused on answers were 'zoomed in.' Their view of the problem space was very limited, and their answers were not well connected to the problem spaces that gave rise to them. They could zoom back out if prompted but it was effortful, and they were unlikely to do so of their own accord. In the following excerpt we see the teacher prompting a zoomed in student to refocus:

LILI: The value of the velocity is getting closer and closer to zero.
TEACHER: on the way up.
LILI: On the way up.
TEACHER: What about on the way down?
LILI: it was getting farther and farther from zero.
TEACHER: Well, what do you mean by away from zero?
LILI: The value is more negative.
TEACHER: That's more consistent with what's on the board. [The object is] moving in the negative direction and faster. Dave, were you going to add something to that?
DAVE: Oh yeah—I was going to say when it's rolling up the hill it's slowing down but when it starts rolling back it's speeding up.
TEACHER: perfect.

Here the teacher redirects the student's attention from the mathematical to the physical interpretation, and he is assisted by Dave, who translates the teacher's statement to something that everyone should be able to understand.

As students became more sophisticated modelers, however, SRs were about constructing useful visualizations of physical situations in order to reason about them. When they reached this stage, the first thing to appear on their whiteboard was the SR, and as it was constructed, its various features and their properties were identified and defined, often in writing. The SR served to keep them zoomed out so that the physical context of the problem remained actively in view in the problem space. Only after this setting of the scene was complete (by the construction of an SR that encoded the elements of the model and their relationships) did students zoom in, abstract out physical quantities, and assemble them into a symbolical representation—an equation. Once they had a sensible equation that flowed from the diagram and obeyed the constraints placed on each of its elements by the definitions and properties that were assigned, they were done. Plugging in actual numerical data and solving for some value was, at times, an afterthought. In some cases, it was not even called for in the tasks students were assigned. *SRs in these instances were for visualizing and making sense of a problem space.*

SRs in this last instance were also an important communication tool in the distributed cognitive sense. There was, at times, a sort of dialogue between the students and their inscription that caused the inscription to evolve as reasoning aloud progressed. In addition to the students working together to create these SRs, the SRs they created functioned as another voice in the exchange of ideas—often a constraining voice that placed limits on the mental models that students were attempting to articulate. One thing that made this dialectic particularly valuable was the opportunity for students to 'interrogate' their SRs. In the following transcript Zane helps an English language learner classmate think about a problem using a variety of written representations:

GUI: What formula do you use?
ZANE: There's no formula that you use. You have to think about this one. Let's think about it. . .it says. . . (looks back at the problem statement in the book). . .the train decelerates at a uniform rate of one meter per second.
GUI: You need to know how long it takes.
ZANE: It doesn't matter.
GUI: But. . .

ZANE: It does not matter. Look. Get this number down to meters per second first. (Points to 72 km/h).
GUI: But...
ZANE: Get it down to meters per second. (After some hesitation, Gui writes 72,000 m/h on her paper, then picks up a calculator, and starts to press buttons.)
GUI: Is it this? (She holds up her calculator for him to see the answer.)
ZANE: No. Okay. Alright. (Takes out a sheet of paper) You've got 72 kilometers per hour to meters per second. Alright? Okay. No, we'll get it to meters first. So...one thousand meters over one k-m equals 72,000 meters for an hour, okay? And then so I want to find...and so there's...in one hour there's sixty minutes, so I divide by 72000 by sixty alright and then there's 60 seconds in one minute. Twenty meters per second. Do you get how I got that? (Gui nods.) So if it's decelerating at one meter per second squared how many seconds is it going to take it to decelerate?
GUI: Twenty.
ZANE: Twenty seconds. That's correct. So it helps to draw a graph. Right here it's cruising at 20 meters per second. Then it slows down (talks as he sketches a velocity time graph for Gui) and then here's that 20 seconds of decelerating right here (draws a diagonal line down to the t-axis) and then it stops for 2 minutes. So how many seconds is two minutes?
GUI: Two minutes?
ZANE: It says it stopped for two minutes.
GUI: One hundred twenty?
ZANE: One hundred twenty. So what's one hundred twenty plus twenty?
GUI: One forty?
ZANE: One hundred forty. There. (He continues to draw the graph.) And then.... (looks back at the book for a moment) and then it accelerates at point five meters per second squared.
GUI: It comes to a stop?
ZANE: Yes it does. It's stopping at a train station for two minutes. This is a time graph. Time-velocity. Okay. So it stops here for two minutes and then it can only accelerate at point five meters per second squared. So it's eventually going to make it's way back up to twenty at point five.

There were many types of questions that students asked in the course of creating and reasoning with SRs. Largely, it appeared that they learned how to ask these questions by imitating the kinds of questioning that their teacher practiced. If the teacher asked fill-in-the-blanks information questions, then that was the kind of questioning they used with each other when creating their whiteboard. If the teacher asked meaning questions or implication questions, then those were the types of questions they were most apt to use with each other when whiteboarding.

Whiteboard sharing with the whole class was substantially different for these two types of collaborations. When SRs appeared first on their whiteboards, students tended to describe how they reasoned through the problem based on their SRs. As a result, they were more apt to be asked questions by other students (or by the teacher) about their diagrammatic choices and interpretations. This resulted in discourse that was more focused on conceptual models and less on procedures. There was rarely a question about a formula or a disagreement about mathematics. When they ran into a physical situation that was counter intuitive, they would zoom in and look to the mathematics for clues about what mattered, but until they reached some impasse, their reasoning stayed connected with the system schema and its physical interpretation when talking about the models they were constructing. Coordination of representations was possible when their SRs had more than superficial meaning to them.

Implications for Instruction

Modeling Instruction can be a powerful instructional practice, but just as in problem solving, we must help students stay zoomed out. Our primary focal plane or frame must be the model—model construction, model elaboration, and model deployment. This is the teacher's problem space. When we zoom in and fix our focus on details such as computation or the meanings of individual words, we signal to our students that this is where their focus ought to be also—this is 'what counts.' That is not to imply that equations and computations are not important, just that they need to be placed in the perspective in the bigger picture. We must never forget to zoom back out to our primary frame—the model—and help students to do so as well.

Novice modeling teachers often describe Modeling Instruction as if it were a technique, a skill, or a craft. They discuss discourse management practices, teacher questioning, whiteboarding rules, grading, using technology, pre-lab demonstrations, tricks for explaining concepts (i.e., negative acceleration, Newton's laws), scheduling and time management, etc. It is easy to fall into the habit of looking at Modeling Instruction in terms of teacher performance rather than student thinking.

One theory about teacher professional development (Fuller & Brown, 1975) suggests teachers go through three distinct phases in learning to teach: concern for self, concern for task, and concern for students. Even an experienced teacher goes through this developmental sequence when they begin teaching something that is new to them. For most teachers, Modeling Instruction definitely qualifies as something new. It is not yet a part of standard teacher preparation programs at the vast majority of colleges and universities in this country. It is not surprising, therefore, that teachers zoom in and focus on their own performance and evaluate it procedurally as if it could be broken down into steps and solved like a mathematics or physics problem. Moreover, once they get comfortable with the procedures that they have identified as modeling, they turn their focus to the task, making the performance of these procedures as technically competent as it can be.

It is not until teachers take that final step of turning their gaze away from themselves and their craft, and toward their students, that they are really engaging in Modeling Instruction. Modeling done well is not about the performance that the teacher turns in on a day-to-day basis—it is about the mastery that the students are able to achieve of the set of models they are constructing and using.

Suggestions for Teachers

What follows is a list of suggestions drawn from this study that may help teachers zoom out and focus on students.

- Design tasks for small group work that focus on probing the problem space rather than tasks that require the use of a certain formula or produce a particular type of answer. Do less of whiteboarding for going over homework and more of whiteboarding for practicing with the model. This means that everyone in the class may be doing the same problem.

- Expect students to lead in board meetings. Hand over the floor to them so that they can take turns as leader and interlocutor. Encourage them to talk to their classmates—not to you. Follow their lead. Prompt rather than grill. When you do enter the board meeting discourse, probe the CS–SR interface—the boundary between saying and seeing. If students are zoomed in on the computation process, help them zoom out by redirecting their gaze to the problem context and physical situation that structure their problem space. And if an important question is on the table, such as when a model applies, do not let them off the hook by answering it yourself. Make them find the answer themselves, even if you have to come back to it later.
- Encourage the students to examine the conceptual system that they bring to their problem space. If they can see that elements of this system are missing from their whiteboards, *they* should add them.
- In reviewing what a group of students has whiteboarded with the whole class, ask them if it contains all the necessary conceptual elements to build a model of the problem at hand. If not, do the students possess the necessary missing conceptual elements and can they activate them, bring them into their conceptual system, and connect them to existing structures in such a way that they are useful for solving problems? If not, are there students in the class who can help them with this process? Encourage them to identify and use the resources that their classmates possess rather than providing them yourself.
- Attend to students as individuals as well as in groups. Learn to watch and listen to what students who are listening to the presentations of others say and do. Are they engaged? Are they perplexed? What are they taking from what is being said? This is hard to do unless we let the students have the floor. When we are on deck, we do not have the attention to spare to focus on individual responses to the discourse. We need to practice 'not taking charge' of the conversation.
- Break the habit of soliciting or listening for particular words, phrases, or answers—particularly when these answers are just two or three words long. Sometimes when teachers hear one or more students answer their question with the 'magic word' (or words) they are listening for, they take it as a signal that they can move on because the students 'get it.' Remember to check on what it is that the student 'gets' and consider checking with the rest of the class to see if they are following this student's line of reasoning.
- Listen for the kinds of things that students think are important enough to question. Where are these things in their concept system? Are they from the CS or the SR? Is the student zoomed in or zoomed out? Change their focal plane and see what happens. Listen for potential gaps in their model that are betrayed by the questions they ask. We must take time to get to know our students—what they value, what they think—what the telltale signs are that reveal when they are bluffing or guessing.

- Ask your students the kinds of questions you would ask yourself if you were trying to set up a problem. Critique them as you would critique yourself. They will learn to critique themselves and others by imitating you.
- Do not let them off the hook by answering important questions for them—and do not move on to a new idea if important questions are not answered to everyone's satisfaction. Make them arrive at the answer themselves—answers they can justify—not just answers they have guessed correctly. Make sure they are convinced and can convince each other that they are reasoning correctly about a situation. Then take the vital step of checking with other students to see if they are convinced. And do not take 'yes' for an answer. Make them articulate what they understand in their own words and listen to see if there are any important elements missing from what they say. Make sure they can zoom in and zoom out without their model falling apart.

Conclusion

The whiteboard is not just a tool—it is a medium for communication, for joint attention, and for cognitive (as well as social) interaction. Whiteboarding is not simply telling what you know, nor is it merely 'show and tell.' It is collaborators interacting at their CS–SR interface to show themselves and one another what they think. Until they can write it down and make a convincing case of their reasoning to their peers, their private mental models remain poorly structured. Whiteboards can afford the necessary platform for representation of the structure of a problem space and help students see the relationships between elements within the conceptual system that they bring to this problem space. Whiteboarding can also facilitate sharing of information and conversion of that information to knowledge that is held in common by members of the group. For the teacher, whiteboarding provides a valuable window on students' perspective within a concept space and an opportunity to help students' reframe this perspective by zooming in or out across the CS–SR interface.

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Chapter 6
The Molecular Workbench Software: An Innovative Dynamic Modeling Tool for Nanoscience Education

Charles Xie and Amy Pallant

Introduction

Nanoscience and nanotechnology are critically important in the twenty-first century (National Research Council, 2006; National Science and Technology Council, 2007). This is the field in which major sciences are joining, blending, and integrating (Battelle Memorial Institute & Foresight Nanotech Institute, 2007; Goodsell, 2004). The prospect of nanoscience and nanotechnology in tomorrow's science and technology has called for transformative changes in science curricula in today's secondary education (Chang, 2006; Sweeney & Seal, 2008).

Nanoscience and nanotechnology are built on top of many fundamental concepts that have already been covered by the current K–12 educational standards of physical sciences in the US (National Research Council, 1996). In theory, nano content can be naturally integrated into current curricular frameworks without compromising the time for traditional content.

In practice, however, teaching nanoscience and nanotechnology at the secondary level can turn out to be challenging (Greenberg, 2009). Although nanoscience takes root in basic physical sciences, it requires a higher level of thinking based on a greater knowledge base. In many cases, this level is not limited to knowing facts such as how small a nanometer is or what the structure of a buckyball molecule looks like. Most importantly, it centers on an understanding of how things work in the nanoscale world and—for the nanotechnology part—a sense of how to engineer nanoscale systems (Drexler, 1992). The mission of nanoscience education cannot be declared fully accomplished if students do not start to develop these abilities toward the end of a course or a program.

A major cognitive barrier for learning nanoscience is the lack of intuition. The nanoscale world is alien to students: electrons, atoms, and molecules are too small to be seen, their interactions resemble nothing in everyday life, and the phenomena are often counterintuitive. This is the world where electromagnetic forces,

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_6,

thermodynamics, and quantum mechanics govern (Drexler, 1988). There is nothing that students can assemble or tear apart with their bare hands in order to learn how these rules work. As a result, the ability to think abstractly is considered as a prerequisite. For this reason, teaching these topics is typically deferred to college level. Even when they are taught at colleges, instructors traditionally rely on some kind of formalism that is heavily based upon theoretical analysis. Clearly, a less steep learning curve is needed for nanoscience education at the secondary level.

Wherever it is unrealistic to engage students with real experiments in the classroom, computer simulations stand out to be an attractive alternative (Feurzeig & Roberts, 1999; Panoff, 2009; Wieman, Adams, & Perkins, 2008). Unlike formal treatments that express ideas through mathematics, simulations express ideas through visualization on display devices and therefore are more likely to be comprehensible and instructive. This simulation-aided teaching is an increasingly important instructional technology as it adapts to today's students who grew up in an increasingly digital world and are more accustomed to visual learning. Good simulations can not only complement formalism to provide an additional, more accessible learning path to difficult subjects such as quantum mechanics (Zollman, Rebello, & Hogg, 2002), but in some cases, replace traditional treatments as a more effective teaching strategy (Finkelstein et al., 2005). In addition, simulations are also cost-effective and scalable. They can be deployed online and run by hundreds of users at the same time.

This chapter presents lessons we have learned through the research, development, and classroom implementation of educational nanoscience simulations using the *Molecular Workbench* (MW) modeling software (http://mw.concord.org) developed by the Concord Consortium (Tinker & Xie, 2008). We hope these lessons will be helpful for science educators worldwide who are interested in adopting and developing interactive science simulations for better education.

Before going into details, we would like to clarify some terminology. The terms we are using are somehow overloaded with a number of subtly distinct meanings. Throughout this chapter, the word *animation* means a planned or scripted display of a sequence of images, the simplest case of which is a video. An animation cannot be changed by the viewer. As a result, all learners will see the same animation. Hence, learning cannot be personalized. The word *computational engine*, or *engine* for short, stands for a computational system that does some calculations to create certain effects or solve certain problems. A computational engine is coded according to some generic scientific laws and therefore is capable of modeling a broad scope of phenomena. The words *model* and *simulation* will be used interchangeably in this chapter to represent an input to an engine that is configured to emulate a real-world scenario. To inform the user, the results of a simulation are rendered as images on a computer screen. These images are often called *visualizations*.

A noninteractive simulation has no fundamental difference with an animation. But an *interactive simulation* has more illustrative power than an animation. Compared with an animation that can only illustrate situations recorded or preprogrammed, an interactive simulation can respond to students' inquiries in all possible ways permitted by the engine. If a picture is worth 1,000 words, you can imagine the information density and intelligence level of an interactive simulation. Furthermore, learning with an interactive simulation delivers a personal experience: each learner controls her/his own pace and manipulates the simulation in a unique manner. Learning through creating a simulation is even more so (Papert, 1991). Each artifact a learner creates records her/his own learning process and contains her/his own thoughts. Empowering an unlimited number of simulations to be created, a good computational engine reflects a similar degree of variety, diversity, and complexity as observed in the real world. Because of its resemblance to a real experiment, a simulation is sometimes referred to as a *computational experiment*.

The word *activity* is used to describe a lesson based on one or more simulations. Besides simulations at the core and their inputs and outputs, an activity may consist of introductory stories, motivating questions, instructions, user interfaces, interactive tutoring, challenges, embedded assessments, and so on. These pedagogical elements scaffold a guided learning space in which the power of simulations can be maximally realized and controlled. Ideally, these elements should be seamlessly integrated with the simulations in the same environment so as to avoid the penalty of context and tool switching.

The Importance of Dynamic Modeling

There are two major types of computer models in most science and engineering disciplines: *data model* and *process model*.

Data models are very common. For instance, Google Earth is a geographic information system driven by a data model consisting of data collected through satellite and land surveys. Those data do not change until the next survey. Another example is the Protein Data Bank that contains tens of thousands of structure data of macromolecules solved from crystallography. The structure data are coordinates (x, y, z) that define the positions of atoms in macromolecules. These data are static, characterizing stable conformations of the macromolecules when they were crystallized to be imaged.

Nature is not static, however. Our world is fundamentally dynamic. It is full of many different kinds of processes—diffusion, creep, flow, growth, propagation, reaction, explosion, and so on. We live in a four-dimensional world (x, y, z, t), not a three-dimensional one. Modeling the four-dimensional world is the purpose of process models. Dynamic modeling is the computational mean of studying process models. From a cognitive point of view, dynamic modeling converts an abstract concept to a salient show on the computer screen. This is already tremendously valuable since it is more likely to convey the knowledge to young learners. Yet the greatest strength of dynamic modeling lies in its capability of reconstructing what has happened and predicting what will happen. A manifest of this capability in the classroom is one of the most exciting and inspiring teaching moments in science education.

In comparison, static data models lack this prediction capability. Molecular visualization (José & Williamson, 2005) is an example that shows the limitation of using only static data model in education.

Since the invention of molecular graphics, a subject that focuses on visualizing molecules using 3D computer graphics, chemists have embraced molecular visualization tools capable of rapidly displaying molecular structures and viewing them from different perspectives. Several free tools have been developed for showing molecules on Web pages (Cass, Rezepa, & Rezepa, 2005). These tools are now widely used by educators to teach molecules.

Most molecular visualization tools, however, are mainly designed to show static structures. The user can rotate and translate the entire structure or change the view angle dynamically to create a motion effect, but the atoms do not move relatively to each other (which is what they are constantly doing in reality). Viewing static structures helps students learn the structures that are represented by data models, but it is often more important to learn the functions that are represented by process models. After all, we study molecules because we hope to exploit what they can do. This is especially true for nanoscience and nanotechnology that have an ultimate goal of creating nanostructures with functions we need. Although one can argue that in many cases there exists a strong structure–function relationship that can help people derive functions from structures, it is inappropriate to expect inexperienced students to be able to reason using the relationship that may be evident only to experts. Too often have we seen an excited chemist trying in vain to explain to nonexperts what he or she sees in a 3D model of a molecule that is beyond a cool picture of some 3D structure to the nonexperts. For example, a buckyball molecule is often used as an icon for nanoscience and there have been a lot of research and applications about it, but few educated people know what on earth this nanosized particle can do except it looks somewhat like a soccer ball. (And by the way, what characteristic feature of a soccer ball gives rise to the utter importance of this beautiful molecule?)

Many basic concepts such as temperature, pressure, interaction, transition, and equilibrium can only be understood in terms of dynamic processes. It is desirable that a molecular process can "speak for itself" through a dynamic model to fill the cognitive gap. Some molecular visualization tools can sequentially display a series of frames, which can be different states of the same molecule observed experimentally or calculated numerically, to create an animation of a conformational change. This is a step forward to help students learn about molecular mechanisms, but it only shows what was set up to happen. For a tool to be more educational, students should be allowed to "mess around" with the models, try many hypothetical experiments, and see what happens. It is during iterations of this type of experimentation that students learn progressively and become inspired. This requires educators to develop computational engines that support interactive simulations of various molecular processes. The more powerful and interactive these engines are, the more students can learn from them. Ideally, they should be just as capable as the tools used by scientists and engineers (Isralewitz, Gao, & Schulten, 2001) and yet as easy to use as a typical computer application designed for average people. Such a capacity will provide unlimited learning opportunities to students and allow them to think and play like professional scientists and engineers. For example, when learning about the buckyball molecule, students can conduct a computational experiment to investigate if the molecule is toxic to human—if it can be easily translocated through a lipid membrane and absorbed into an animal cell (Wong-Ekkabut et al., 2008). The inquiry at this level is much more profound than any possible inquiry design based on having students look at the static structures of the Buckminster fullerene and a lipid bilayer and then try to reason about their interactions.

Why Use First Principles to Build Educational Simulations?

A first principle is a foundational scientific law from which many phenomena can be explained and many propositions can be derived. For example, Newton's equation of motion is the first principle in classic mechanics—everything in the domain of classic mechanics can be explained by solving it using numerical simulation. This of course is the holy grail of science. But it is also important to emphasize the educational significance of simulations built from first principles.

The educational software market is largely dominated by cartoon movies, animations, and games. Many of these media were usually produced with visual effects as the paramount design goal in the developers' minds. There is seldom a need to exploit advanced mathematics and computation based on first principles. If the effective use of this power requires substantial training and investment, few commercial producers of educational media would be willing to take the financial risks. But this may change soon in science education, enlightened by the success of recent "killer applications" to be discussed below.

A strand of educational simulation programs for teaching mechanics, started with *Interactive Physics*[1] back in the 1990s and significantly advanced by the recently released *Algodoo*[2] and *Crayon Physics*,[3] have demonstrated great educational potential. These impressive programs allow users to draw a variety of 2D shapes, which then move realistically on the screen: they fall, slide, roll, and bump into each other—just like objects in the real world they model after do. These programs have a user interface that is very friendly to novices, especially with a freehand drawing tool connected to a digital pen on a tablet PC. With only a handful of tools, users can sketch up many interesting 2D simulations. Experienced users can build high-grade simulations as sophisticated as a vehicle impact test and a hovercraft takeoff. It is probably not an exaggeration to say that what users can create is limited only by their imagination.

There is no doubt that these entertaining tools truly motivate students, unleash their creativity, and make learning mechanics unprecedentedly enjoyable. But the important thing is that all these would not have been possible without using some high-end computational mechanics. The reason that these tools model the real world so well is because the motions of objects are calculated by solving Newton's equation of motion—to be more precise, using a computational method

[1] http://www.design-simulation.com/ip/index.php

[2] http://www.algodoo.com

[3] http://www.crayonphysics.com

commonly known as multibody dynamics (Amirouche, 2006). In fact, *Algodoo* uses a computational engine called *SPOOK* developed by Dr. Claude Lacoursière (Lacoursière, 2007), and *Crayon Physics* uses a similar one called *Box2D* developed by Dr. Erin Catto (Catto, 2007). These multibody dynamics engines simulate interconnected bodies with contacts, joints, constraints, dry friction, and power input/output. *Algodoo* even has multiphysics capability by integrating multibody dynamics with the smoothed particle hydrodynamics for modeling fluids (Liu & Liu, 2003).

The multibody dynamics method was, however, not intended to be used in education. It was developed to design robots, vehicles, aircraft, and so on. The generations of computational scientists who contributed to the method presumably did not anticipate that one day the method would find its place in hundreds of thousands of middle and high schools all over the world. By the time we were writing about this, the total count of the floating point operations run in classrooms commanded by the educational tools mentioned above might have far exceeded that of those carried out for research in labs from all over the world added up together.

What does this teach us?

The first lesson we learned is that computational science is not a privilege of some scientists in ivory towers or engineers in the defense industry any more. In fact, science education and scientific research share a common goal: to understand how things work. It is, therefore, not surprising that a research tool like multibody dynamics can be so successfully converted into an effective learning tool. We would further contend that the only correct way to develop an educational tool would be to use the first principles in the corresponding domain of science as much as possible. The initial investment on such a tool may be high and risky (e.g., it needs dedicated computational scientists and programmers like those unsung heroes behind *Algodoo* and *Crayon Physics* to take their own risks for their careers), but the payback will be more powerful, useful software that can last for a long time and extend their outreach to millions of students worldwide.

The single most important reason for using first principles to build educational tools is that the power of creation and prediction embodied in these scientific principles will be given to *every* student. Such a tool can help students appreciate the unity of science—that everything can be derived from some commonality however their appearances and representations may differ. This is the most profound nature of science. What else is more important in education than passing students the greatest power and deepest wisdom brought to us by the most brilliant figures of the entire human race in hundreds of years? Now that the information technology has empowered us to deliver these intelligences through computing, an unprecedented opportunity to revitalize science education using this enabling technology is right upon us.

Unfortunately, this opportunity is often underappreciated in the educational world. The vision that the much-advocated cyberlearning infrastructure (Borgman et al., 2008) should include smart media powered by first principles is not widely shared. Using computational science to build interactive media is not part of the design guidelines for the mainstream. Applications such as *Algodoo* and *Crayon*

Physics are still scarce. There are many more domains of science and engineering that need to be covered. Enormous volumes of literature have existed for how to simulate real-world problems by numerically solving fundamental equations such as the Navier–Stokes equation for fluid dynamics and the Maxwell equations for electromagnetism and photonics. Sadly, there has been little investment and interest in making those powerful methods usable by students and the public at large, even in the face that the foundation of simulation-based engineering and science that gave birth to those methods is rapidly eroding due to the lack of student interest at the secondary level (NSF Blue Ribbon Panel on SBES, 2006).

Outside education, game developers have adopted first principles far more quickly and aptly. Games need to have realistic look-and-feels in order to be competitive in the market that always demands better realism. Major graphics libraries already provide excellent lighting functions. Realistic motions and flows powered by real-time physics engines (Bourg, 2001) and fluid solvers (Stam, 2003) are now not uncommon in games. *Algodoo* and *Crayon Physics*, despite their great educational power, are often billed as games. Hopefully, foundational open-source code libraries will be developed by the game industry and proliferate to eventually benefit educational software developers and changes will then occur.

The Molecular Workbench Software

Nanoscience education aims at cultivating students' ability to reason about complex phenomena based on first principles governing the structures, interactions, and dynamics of electrons, atoms, and molecules. Dynamic modeling of nanoscale phenomena based on first principles provides a direct approach to making nanoscience more accessible and teachable in the classroom. Dynamic models render rich, salient views of the behaviors and interactions of electrons, atoms, and molecules that no microscope or ultrafast spectroscopy today can easily capture (see Fig. 6.1 for an example of water movement in a carbon nanotube). Through a carefully designed graphical user interface, a simulation tool allows students to manipulate a computational model, conduct various "what-if" computational experiments, and even design new simulations to test their own hypotheses.

Computational nanoscience (Rieth & Schommers, 2006; Wilson, 2003) involves sophisticated calculations using numeric methods such as molecular dynamics and quantum chemistry (Leach, 2001; Rappaport, 1997). These methods used to run on high-end computers that were not accessible to most students. But the computational power of ordinary computers today has increased to the point that these intensive computations can now be done on them to produce comfortable visualizations in real time. As computer power continues to be multiplied by multicore computing and supplemented by graphical processing units, it looks more and more feasible to create computational labs that complement wet labs in teaching and learning nanoscience.

The *Molecular Workbench* modeling software represents a decade-long effort toward the realization of this goal. Created from scratch using the Java programming

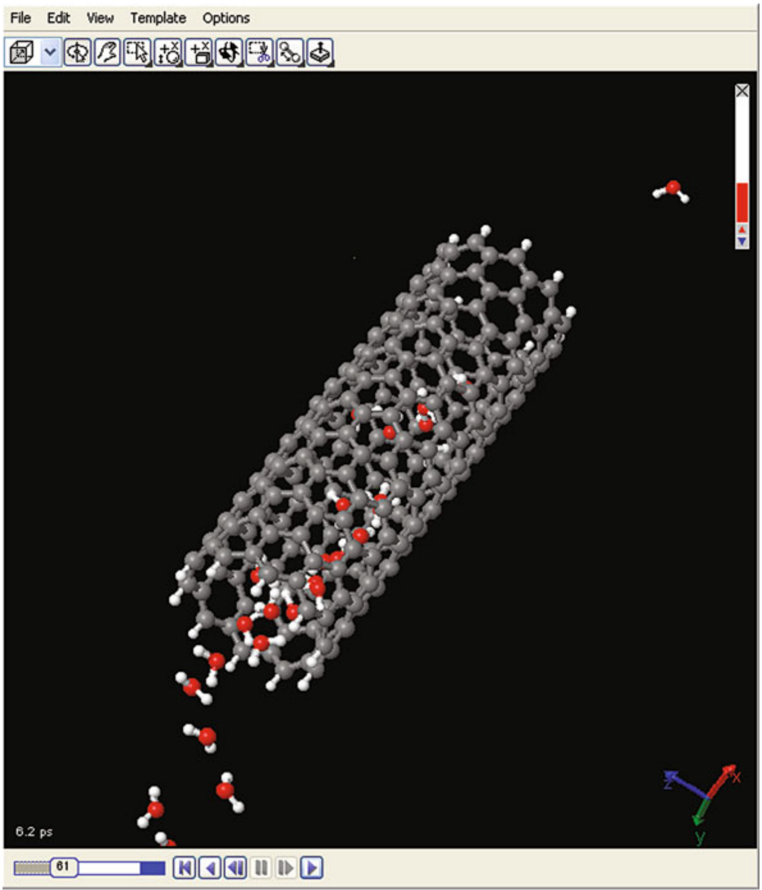

Fig. 6.1 A screenshot of a molecular dynamics simulation of water molecules moving in a carbon nanotube using the 3D molecular dynamics simulator of MW. This simulation can be used to illustrate the purification of water using nanotube filters

language, MW is a sophisticated software system that includes the modules discussed in the following sections.

The Computational Engines

MW's modeling power comes from its computational engines, two of which simulate phenomena at the nanoscale.

The Molecular Dynamics Engine

The classic molecular dynamics engine in MW calculates the forces on atoms based on the interatomic interaction potentials such as van der Waals potential, electrostatic potential, and covalent bonding potentials (Xie & Tinker, 2006). The trajectory of each atom is then predicted by solving Newton's equation of motion based on the calculated forces on it. The results of the atomic motions are immediately rendered by using Java's graphics library and shown on the screen. The calculation and visualization are done in different threads so that a simulation utilizes both CPUs on a dual-core computer, which most computers today are. As a simulation runs in real time, the user can interact with it any time and see its response right away, making inquiry a straightforward process. This is a fundamental difference between the molecular dynamics engine in MW and other molecular dynamics programs that were not developed for education.[4]

Based on Newton's equation of motion, the molecular dynamics method guarantees a great deal of scientific integrity:

- *The First Law of Thermodynamics.* This law, also known as the Law of Conservation of Energy, is automatically satisfied in a molecular dynamics simulation for an isolated system. If there is no energy input/output through external forces or dissipation through friction, the total energy, which is the summation of the potential energy and the kinetic energy for all the atoms in the system, remains constant within the tolerance of numerical errors. This can be used to check if a simulation runs properly.
- *The Second Law of Thermodynamics.* Molecular dynamics simulations of basic processes such as diffusion, heat transfer, and phase transition clearly show that the entropy of an isolated system always tends to maximize. In spite of the fact that it is possible to deliberately create special initial conditions that lead to a process of entropy reduction in an isolated system, in practice we have never found that such a condition can spontaneously arise during a simulation.
- *The Law of Momentum Conservation.* As the Law of Conservation of Energy, this law is also automatically satisfied in a molecular dynamics simulation. Together these two laws are responsible for making each collision among atoms look right on the screen.
- *Other Laws.* A number of laws and conjectures in physics and chemistry that summarize insightful observations by generations of scientists, such as the Ergodic Hypothesis, the Theorem of Energy Equipartition, the Reversibility Paradox, Maxwell's Theorem of Speed Distribution, the Boltzmann Distribution, Fourier's Law of Heat Conduction, Raoult's Law, Van't Hoff's Law of Osmosis, Pascal's Principle, Archimedes's Principle of Buoyancy, and all the gas laws, can all be tested or proven using molecular dynamics simulations.

These laws and conjectures have been used as test cases for the molecular dynamics engine in MW to ensure its correctness. If knowledge is power, you can imagine how much power is made accessible to students when they have the molecular dynamics tool to play! Once again, this educational potential would not have been possible without the application of first principles.

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[4]For instance, see Gromacs: http://www.gromacs.org

The Quantum Dynamics Engine

Quantum effects are fundamentally important in the nanoscale world.[5] Although quantum phenomena are very hard to understand, they are undeniably real and ubiquitous. Teaching quantum mechanics is so challenging that many nanoscience education programs choose to just scratch its surface or simply avoid it all together. How can we teach quantum reasoning to students without getting them bogged down in the complex mathematics of quantum mechanics and, quite possibly, the philosophical questions associated with its weird interpretations that are still at issues among scientists and philosophers? Recognizing all these learning difficulties, we set out to explore if computer simulation can deliver a pragmatic solution for *all* students to develop some quantum sense without having to learn through difficult mathematics.

Again, our strategy is to use first principles in quantum physics to build a simulation system that can teach. The quantum dynamics engine in MW solves the *time-dependent* Schrödinger equation using a fast and stable finite-difference time-domain algorithm (Watanabe & Tsukada, 2000). As with the molecular dynamics engine, a quantum simulation is performed in real time. The propagation of the wave function is calculated based on the Hamiltonian operator obtained from the potential fields contributed by objects that represent atomic and molecular structures. The calculated wave function at each time step is visualized on the screen immediately, rendering a continuous motion of the electron wave. Students can intervene at any time to adjust the potential fields or apply an external electromagnetic field and observe the change of the electron wave right away.

We would like to point out the value of dynamic modeling afforded by our quantum dynamics engine (see Fig. 6.2 for a dynamic model of the scanning tunneling microscopy). Most quantum mechanics simulations for education are based on solving the *time-independent* Schrödinger equation (Zollman et al., 2002). Often, the visualization shows some stationary wave functions such as an atomic orbital. Visualization of stationary wave functions suffers from the same problem as with visualization of static molecular structures. The shape of an atomic orbital contains the information about the spatial probability distribution of electrons at certain energy level. Very little can be inferred from that piece of information. The result is that in many chemistry classes students are asked to memorize the shapes of the s, p, and d orbitals without necessarily understanding the implications of them.

The quantum dynamics engine is capable of simulating a variety of dynamic quantum processes: bound state, excited state, quantum transition, the formation of a covalent bond, chemical polarity, field-induced polarization, ionization, diffraction, interference, tunneling, quantum transport, and more. It is fascinating to see that these seemingly disparate concepts in physics and chemistry just emerge from quantum dynamics simulations that are based on a few basic assumptions—that electrons are represented by moving waves and the waves interact with each other

[5] "We have become quantum mechanics – engineering and exploring the properties of quantum states. We're paving the way for the future nanotechnicians." — Donald M. Eigler, IBM Fellow

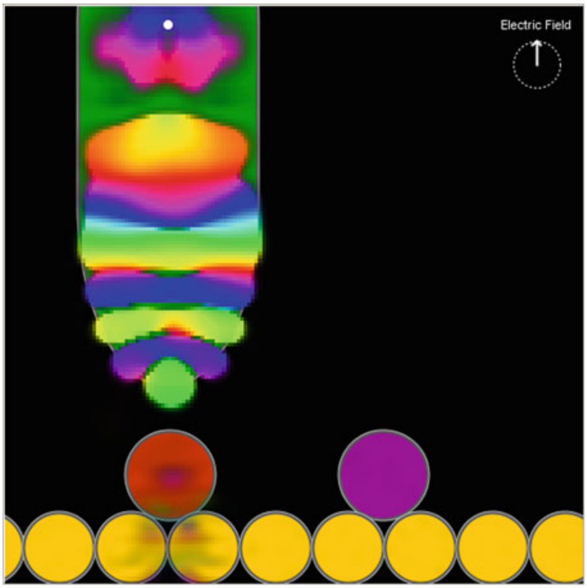

Fig. 6.2 A screenshot of a quantum dynamics simulation of a scanning tunneling microscope that is an important tool in nanoscience. The wave function (colored by the phase) propagates in the tip and tunnels through the vacuum between it and an atom on the surface of a substrate, creating a weak electric current

and nuclei through electrostatic interactions! In fact, the quantum explanation of chemistry is among the greatest scientific discoveries in the twentieth century, which was witnessed by several Nobel Prizes awarded to computational chemists.

The Modeling and Authoring System

A unique strength of MW lies in its deep root in the software architecture that was designed to support model construction and activity authoring. Unlike tools that just offer existing simulations, MW gives the entire power of creation to users of different levels, in addition to a myriad of existing simulations available through it that anyone can pick up to use in the classroom. The constructionism strategy of engaging students to design simulations and teachers to create activities has been proven effective by a series of important work originated from MIT's Media Lab through a product line starting from *Logo* to *Scratch* (Colella, Klopfer, & Resnick, 2001; Kafai & Resnick, 1996; Monroy-Hernández & Resnick, 2008; Wilensky & Reisman, 2006). This capacity extends the application of MW beyond a provider of interactive simulations. Given the successful example of *Algodoo* and *Scratch*, further development of MW in this direction seems very promising. If at the macroscopic level multibody dynamics and fluid dynamics govern, then at the nanometer level the rulers become molecular dynamics and quantum mechanics. This perspective places MW at a strategically important position to become a universally useful tool in nanoscience education.

The designing of a simulation, which we call modeling, and the designing of an activity, which we call authoring, are the two distinct levels of creation in MW.

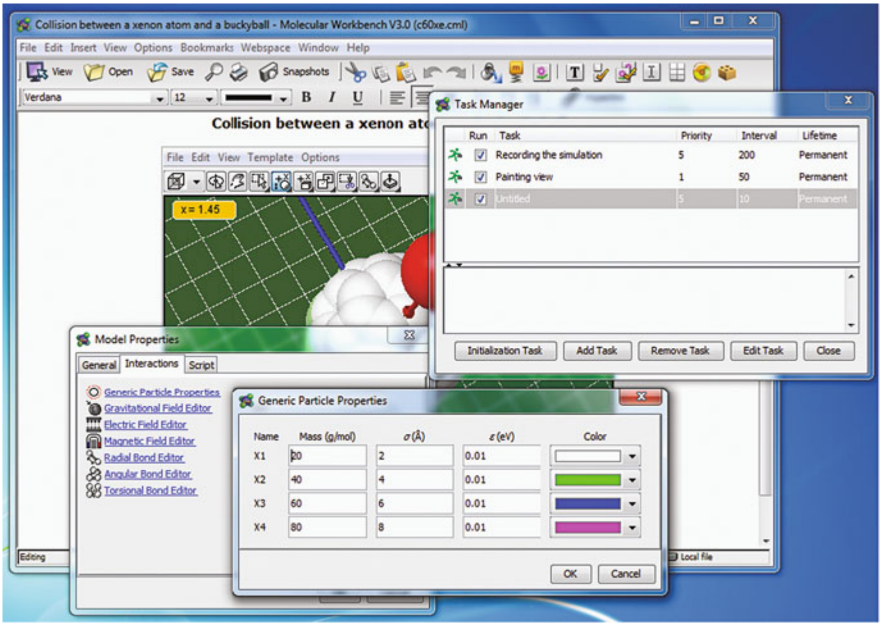

Fig. 6.3 A screenshot of MW in the editing mode for creating a simulation-based activity, taken on Windows 7

At the modeling level, each computational engine in MW has its own set of user interfaces uniquely designed for building simulations of the corresponding type (see Fig. 6.3 for the user interfaces for creating 3D molecular dynamics simulations). At the authoring level, the user can create an activity by inserting a simulation and then setting up the pedagogical elements and assessment items around it.

For both levels, graphical and drag-and-drop user interfaces were developed to allow entry-level users to get started with simple designs. For instance, with the interfaces for creating a molecular dynamics model, users can insert atoms and molecules, create bonds, apply external fields, set up boundary conditions, change temperature distribution, assign charges, add other objects such as images, lines, rectangles, ellipses, and triangles, copy/cut/paste/translate/rotate an object, edit properties of each object, and so on. With the interfaces for creating an activity, users can insert all types of standard components—buttons, check boxes, radio buttons, combo boxes, sliders, and spinner buttons—that can be used to interact with a simulation. Common data visualization components such as line graphs, bar graphs, and gauge graphs are provided to display outputs from a simulation. Widgets such as multiple-choice questions and open-ended questions are available to design embedded assessment. An embedded assessment question can be placed right next to a simulation to form a compact user interface for interacting and learning.

Acknowledging the limitation of graphical user interfaces and the time constraint in perfecting them, a scripting environment was engineered to augment them. Based on an interpretive scripting language, this environment allows advanced-level users to design customized simulations and activities. For a simulation to have a customized emerging behavior, a scripted custom task can be added to the task pool of an engine. For an activity to have a customized user interface, scripts can be set for its widgets to customize the interactions they invoke. This feature of the MW system is particularly useful as it gives advanced-level users the ability to do anything allowed by the scripting language.

In addition, MW is an extensible platform that supports plug-ins written in Java such as an applet. This makes it possible for any author to easily incorporate as many types of computational engines he or she needs without compromising the stability of the main system and other modules or engines. As a matter of fact, the entire quantum dynamics engine was designed as an applet that runs in both an MW and a Web browser.

The Delivery System

MW simulations and activities can be deployed in a number of different ways. Depending on the need of the educational developers who use them, there are three main ways to publish an MW creation:

- *Java Web Start*: An activity can be delivered through the Java Network Launching Protocol (JNLP) supported by most servers and browsers. Once a JNLP link is clicked on a Web page, MW will be automatically launched to load the activity.
- *Applet*: An activity can be deployed on the Internet as an applet. Users can insert an MW applet in a Web page, a forum thread, a blog entry, or a Wiki page, and use JavaScript to integrate it with other Web applications written in Ajax and HTML5.[6] This capacity allows an educator to use any MW simulation on his/her own educational Web sites.
- *Embedded software*: MW is a Java system that can be conveniently used as a piece of embedded software in any open-source Java project.

The flexibility of deployment addresses different needs of educators and therefore opens up opportunities for wider adoption and dissemination of MW simulations and activities.

The Assessment System

MW has a unique assessment system that is an integral part of the software. It supports standard instruments such as multiple-choice questions and open-ended questions. The most important innovation of the assessment system is the image question, which is our original contribution and will be introduced in the following.

[6] http://molecularworkbench.blogspot.com/2010/02/mwscript-javascript-interaction.html

The proverb “a picture is worth a thousand words” underpins the importance of visualizations in science education. Visualizations of large amounts of complex data can effectively convert the information into recognizable patterns that can be absorbed by students quickly. A picture is worth a thousand words for assessment, too. As much as the visualization of a science concept helps students gain a deep insight about it, the visualization of a student’s work can help researchers gain a deep insight about how students learn. The visualizations created by students reveal what they observe, how they interpret the data being visualized, and which levels of their understandings about the concepts are. Analyzing these results, important feedback can be provided to curriculum developers about how well the learning goals have been achieved, to teachers about what their students have learned, and to researchers about how effective the pedagogy is.

An image question has a question, which is set by a curriculum developer, and a container, which a student can fill with a snapshot image taken from a simulation to answer the question (see Fig. 6.4). A snapshot image can be annotated

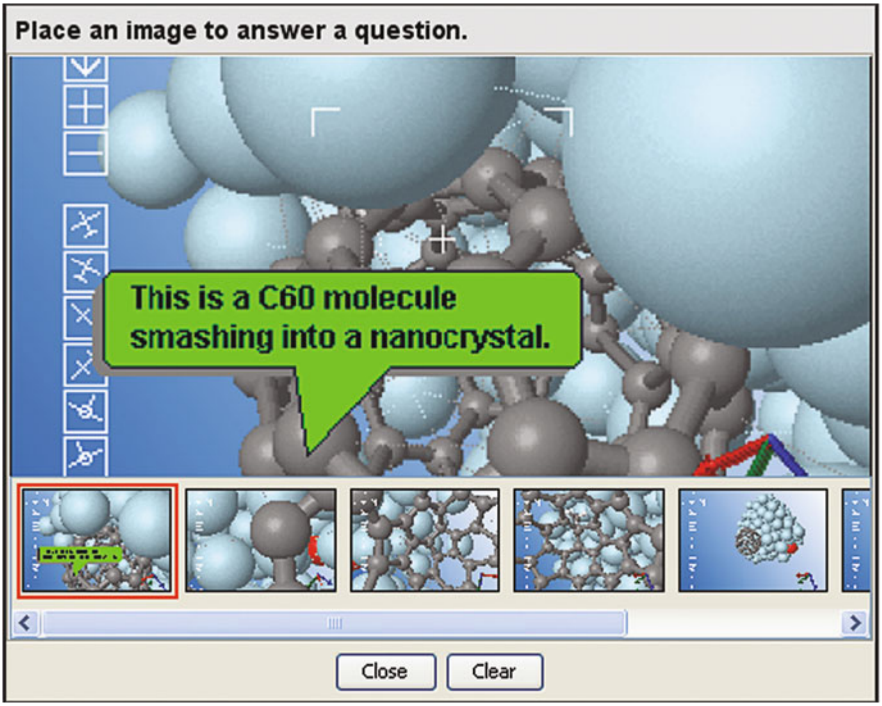

Fig. 6.4 A screenshot of an image question. The student has to take a number of snapshot images that record his/her observation with a simulation and pick one that best answers the question. In the above image, the *lower panel* shows the thumbnails of some snapshot images taken in a hypothetical learning situation, from which the student will drag one and drop into the middle panel to make a selection. The text box is an annotation that was added to the snapshot image to mark an observation

using a simple editing tool, which allows the student to write text and draw shapes. Answering an image question is similar to answering an open-ended question, except that the student generates an image instead of writing some text. A snapshot image the student chooses carries a lot of information that can be used to analyze the student's learning, especially when it is annotated.

Compared with other research instruments, the image question has several advantages. First, the best way to study the effectiveness of visualizations is to use the visualizations themselves. The image question provides a tool for students to describe, explain, and show what they learn from visualizations, using a snapshot tool that captures a scene of interest and an annotation tool that highlights the details on top of a snapshot image. Students thinking can therefore be made visible, assessable, and measurable. Second, the image question provides more reliable data for assessment. Unlike a multiple-choice question that could be randomly guessed and an open-ended question that could be "answered" through copy-and-paste, an image question can only be answered using an image that the student must take himself/herself during an activity. Third, the image question is more engaging to the student. Its intuitive graphical user interface allows the student to easily drag a thumbnail image from the snapshot gallery and drop it into the container.

Students' images for an image question are included, along with their answers to other types of questions, in a report that can be submitted or printed at the end of an activity. Their teachers will be notified of submissions and have access to students' work.

Results

By the end of 2009, MW has been downloaded over 500,000 times worldwide. Educators from all over the world have translated existing MW activities or developed their own in several languages including Chinese, Russian, Portuguese, Spanish, Italian, Hebrew, Norwegian, and Thai. Nearly 2,000 simulations and activities from students and teachers have been submitted to our databases. MW simulations have probably been run millions of times and benefited numerous students. It has also become instrumental in teaching molecular modeling at colleges and universities (Jensen, 2010).

At the Concord Consortium, we have conducted several studies on student learning using MW activities, covering a broad range of content and involving students from middle school to community college. The results demonstrated that students who used well-designed activities achieved a solid understanding of atomic-scale phenomena and were able to transfer the knowledge to new contexts (Pallant & Tinker, 2004). In a retention study, volunteers participated in an interview and responded to a questionnaire about retention of core concepts 2–6 months after having completed activities in their classrooms. The study focused on how the modeling activities and in particular the visual representations aided student retention of concepts over time. Students were shown a screenshot of the model and prompted to describe the concepts being taught, the model parts, and the relationship to the instructional content. All students could identify the key concept, 86% could describe what all the different parts of the model represented, and 57% could elaborate on the concept and the importance of the interactions with the model. This study clearly indicates that students retain vivid memories of their interactions with the models and of the concepts. Although these studies are not directly related to nanoscience education, the results may still shed light on how nanoscale simulations can enhance learning.

In an independent study, Moher and collaborators used MW to engage students to design self-assembling nanostructures (Shipley & Moher, 2008). Their results showed that students demonstrated the ability to design nanoscale models using the tool and highlighted the value of the construct-centered design methodology in learning nanoengineering (The National Center for Learning and Teaching in Nanoscale Science and Engineering, 2008).

We have also collaborated with chemistry professor Dr. Neocles Leontis at Bowling Green State University (a science teacher preparation institution in Ohio) to pilot test the constructionist strategy in his general and physical chemistry course. Professor Leontis challenged his students to answer questions by designing MW simulations. These questions would not have been able to be answered before, because high-level analytical skills involving advanced mathematics were needed. But because MW is a modeling tool for solving complex problems without using complicated mathematics, he did not have to worry about his students' mathematical backgrounds.

The results of this case study have been phenomenal (Xie & Pallant, 2009). Two classes of students submitted nearly 150 simulations, some of which have such brilliant designs that even we had never thought of before. We found no evidence that students would just duplicate each other's simulations and converge to the same ideas. In a challenge that asked them to come up with models that prove or disprove the Ideal Gas Law, students were capable of creating various simulations that attack the problem from different directions. Other design challenges included inventing nano purification devices and creating insulation blocks and thermal bridges to control heat flow at the nanoscale. It is evident that these design challenges succeeded in engaging students and greatly enhanced their analytical and problem-solving skills. The following is a testimonial from a student who created a simulation of fuel cell:

> *Molecular Workbench* is something that I think all physics and chemistry classes should have because it gives an alternative way to grasp concepts outside of just lecturing in the classroom. It allowed me to explore in a way unimaginable before when I built a fuel cell simulation step by step myself. In essence, I could let my curiosity flow by exploring how each editing tool affected my creation. Sometimes I could not figure out how to build it myself, but the program was designed in a way that would not stop my acquisition of learning. Since it is set up like a learning community, I could view someone else's idea of how it should look. In this, I learned in two ways, by attempting my own simulation and by analyzing others. —*Britiany Sheard, student, Bowling Green State University*

This level of success would have been quite improbable using traditional teaching methods in a physical chemistry course.

Future Work

Despite of the fact that dynamic modeling can foster student learning, there are some caveats. No matter how good a computer simulation is, it is in general not appropriate to replace real hands-on experiments with it. The recent virtualization trend in science education has prompted the American Chemical Society to issue a statement that suggested that in academic transcripts simulations may not substitute lab work (American Chemical Society, 2008).

While most educators agree that simulations should be helpful, extensive research needs to be carried out to substantiate the effectiveness of learning through simulations, to analyze the interplay between learning in the virtual world and learning in the physical world, and to learn how to take advantage of the strengths of both (Steinberg, 2000). Results from research in this direction will hopefully provide valuable feedback to developers and make technology work even better in the classroom.

Acknowledgment This work is supported by the National Science Foundation under grant number DUE-0802532.

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Chapter 7
Lowering the Learning Threshold: Multi-Agent-Based Models and Learning Electricity

Pratim Sengupta and Uri Wilensky

Introduction

Electromagnetism, in particular, electricity, is a notoriously hard topic for students at all age levels (Belcher & Olbert, 2003; Cohen, Eylon, & Ganiel, 1983; Eylon & Ganiel, 1990; White, Frederiksen, & Spoehr, 1993; etc.). The difficulty in understanding basic phenomena such as electric current, electric potential difference (or voltage), electric resistance is often displayed in the novices' explanations involving behavior of simple electrical circuits. Furthermore, misconceptions that stem from these difficulties have been regarded by several researchers as resistant to change due to instruction (Cohen et al., 1983; Hartel, 1982) and indicative of a discontinuity between expert and novice knowledge systems (Chi, Slotta, & Leauw, 1994; Reiner, Slotta, Chi, & Resnick, 2000).

Our prior work has shown that the problems faced by novice learners in the domain of electricity can also be understood in terms of the difficulties faced by novices in understanding behaviors of a *complex system,* i.e., systems in which phenomena at one level *emerge* from interactions between objects at another level (Sengupta & Wilensky, 2009; Wilensky & Resnick, 1999). For example, a traffic jam can be considered an aggregate level phenomenon which arises form simple interactions (such as moving forward, braking) between many individual level agents (i.e., cars). In this chapter, we build on this research and demonstrate how a suite of emergent, multi-agent-based computational models (NIELS: NetLogo Investigations in Electromagnetism; Sengupta & Wilensky, 2008a, 2008b) can be designed to represent electricity in linear resistive systems in a manner that is intuitive and easily understandable by a wide range of physics novices: from 5th-grade to 12th-grade students.

At the heart of our thesis is the idea that such an emergent perspective enables novices to develop an understanding of electrical conduction by bootstrapping, rather than discarding their intuitive knowledge (Sengupta & Wilensky, 2009; under

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_7,

review). NIELS models are based on Drude's microscopic theory of electrical conduction, which presents an emergent picture of electrical conduction. We discuss the epistemic affordances and challenges of Drude's microscopic theory of electrical conduction, specifically in the context of middle and high school learners' development of understanding of electric current as a "rate." We then present a specific NIELS model and show that how it was (re)designed and appropriated to address these challenges for learners 5th, 7th, and 12th grades. Finally, we present the effectiveness of our design approach by showing (a) how learners developed understandings and explanations of electric current in linear circuits by coordinating their intuitive knowledge at the agent level through interacting with the relevant NIELS model(s) and (b) how the same NIELS model lent itself to different curricular constraints and epistemological needs of learners in middle school and high school classrooms.

Theoretical Overview: Electricity and the Micro–Macro Link

Misconceptions in Electricity as "Slippage Between Levels"

The source of students' difficulties in understanding introductory electricity (i.e., macro-level phenomena such as behavior of electric current in electric circuits) has been explained in terms of a "missing macro micro link" between the domains of electrostatics and electrodynamics (Eylon & Ganiel, 1990; Sengupta & Wilensky, 2009; White & Frederiksen, 1998). This can be explained as follows: Traditional classroom instruction in electricity is typically segregated into two domains—electrostatics and electrodynamics. Electrostatics is the study of how stationary electric charges interact with each other, and electrodynamics is the study of the behavior of moving electric charges in electric and magnetic fields. Studies also show that students find electrostatic interactions between a few charges easy to understand (Cohen et al., 1983; Eylon & Ganiel, 1990; Frederiksen, White, & Gutwill, 1998). But introductory concepts in electrodynamics such as electric current, resistance, and potential difference are primarily represented in terms of the symbolic, mathematical derivations of Ohm's law, and the connections with electrostatics are not made explicit during instruction (Eylon & Ganiel, 1990; Frederiksen, White, & Gutwill, 1999; Belcher & Olbert, 2003). Even in laboratory experiments that accompany such theoretical instruction, students typically operate an ammeter and/or a voltmeter (instruments that measure amount of current and voltage, respectively, across a conductor) in a circuit where a wire (resistor) is connected across the two ends of a battery. Therefore, students, after such instruction, are unable to relate behavior of individual charges within the wire at the microscopic level (such as electrons and ions) to the macroscopic level behavior (such as electric current, resistance).

A large body of research has focused on the content and structure of the initial conceptual knowledge of physics novices in the domain of electricity. This work can be summarized as follows: first, research over the past three decades has shown that

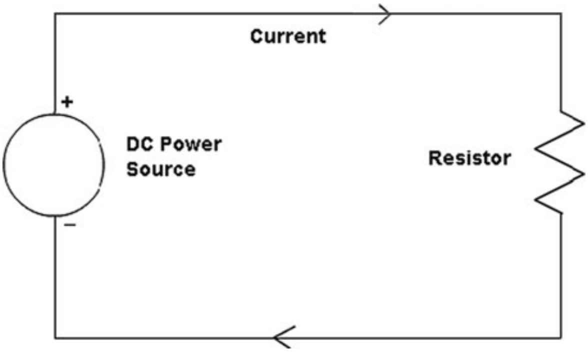


Fig. 7.1 A linear electrical circuit with a single resistor

students at all levels—middle school through college—find basic electricity hard to understand (for a review, see Reiner et al., 2000); second, the reason for this difficulty has been predominantly attributed to the incompatibility between naive and expert ontology (Reiner et al., 2000; Slotta & Chi, 2006; Chi, Slotta, & Leauw, 1994); and third, although a few researchers have argued for incorporating a microscopic perspective in electromagnetism education, these arguments have been so far limited to advanced high school and college settings and have predominantly used an equation-based approach (Chabay & Sherwood, 2000; Haertel, 1987, 1982).

Consider, for example, a simple linear circuit shown in Fig. 7.1. Research shows that most novices typically reason that current *coming out* of the circuit is less than that *going in* (Reiner et al., 2000). That is, when current coming out of the battery meets the resistor, it slows down and/or some of it is "lost" in overcoming the resistance. This type of reasoning has been termed as "current as an agent" model (White & Frederiksen, 1992), as well as "sequential reasoning" or the "current wearing out model" (Dupin & Joshua, 1987; Hartel, 1982).

According to Reiner et al. (2000), these misconceptions indicate that naïve conceptual ecology in the domain of electricity is based on a coherent knowledge structure - object schema - that includes ontological attributes of objects such as "being containable," "being pushable," "storable," "having volume" and "mass," "being colored." They argue that experts think of electrical phenomena in terms of "process schemas" (Chi et al., 1994) or "emergent processes" (Chi, 2005; Slotta & Chi, 2006), and that naive ontology is incompatible with expert ontology. Based on this, Chi and her colleagues argued it is that only by discarding naive ontology that one can engender expertise in novices. They have argued for direct instruction focused on teaching the "process based" or "emergent ontology" (Chi, et al., 1994; Slotta & Chi, 2006) as the suitable method to teach electricity to novices.

In a recent paper we proposed an alternative cognitive model of naive misconceptions in electricity (Sengupta & Wilensky, 2009). We argued that commonly noted naive "misconceptions" of electric current and related phenomena can be better understood as behavioral evidences of *slippage between levels*—i.e., these misconceptions occur when students carry over object-like attributes (e.g., blockage, flow) of the individual agents (e.g., electrons in a wire and charges in battery terminals) to the emergent macro-level phenomena (e.g., current). In that paper, we reported results of a pilot implementation of two earlier versions of NIELS models in an undergraduate physics course. In the first model students investigated electrostatic behaviors of two electric charges, and the second model simulated a continuous flow of electrons resulting form an aggregation of electrostatic attractions and repulsions. After interacting with these models, students were able to develop a deep understanding of electrostatics and electric current by "bootstrapping," rather than "discarding" their existing repertoire of intuitive, object-based knowledge. We found that the same object-based, naive knowledge elements that Chi and her colleagues found to be detrimental to learning electricity and incompatible with expert ontology, were, in fact essential components of learners' correct explanations (in the post-test) about electric current and voltage. But, the important difference was that these knowledge elements, instead of being activated only due to macro- or aggregate-level cues (as was evidenced by the participants' pre-test responses), were activated due to micro- or individual-level cues in the post-test. Furthermore, we also found that participants' post-test explanations that involved process schemas at the aggregate-level of description of the phenomena, often involved several object-schemas at the individual level of description of the same phenomena.

The "Emergent" Approach: The Microscopic Theory of Conduction and Its Affordances

The "emergent" approach toward teaching and learning electricity that we have argued for elsewhere (Sengupta & Wilensky, 2009; under review; Sengupta, 2009) rests on the microscopic theory of electrical conduction. It was first proposed by the physicist Paul Drude (1900) and is now typically taught at undergraduate and graduate levels (Chabay & Sherwood, 2000; Ashcroft & Mermin, 1976). At the heart of Drude's theory is the notion of free electrons, which are the electrons in the outermost shell of a metallic atom (Fig. 7.2). When isolated metallic atoms condense to form a metal, these outermost electrons wander far away from the parent nucleus, and along with other free electrons, form a "sea" or a "gas" of free electrons. The remaining "core" electrons remain bound to the nucleus and form heavy immobile ions. In the absence of an electric field, collisions with these ionic cores give rise to a random motion of the electrons. When an electric field is applied to this "gas" of free electrons, the electrons try to move against the background of heavy immobile ions toward the battery positive. It is the aggregate effect of these electron–ion collisions that give rise to electrical resistance, whereas electric current is the net flow of electrons resulting from the aggregate motion of individual free electrons. The interested reader can find a more detailed qualitative as well as quantitative discussion of Drude's theory in Ashcroft and Mermin (1976; pp. 24–49).

Let us now consider "n" free electrons in a unit volume of a wire, each moving with a velocity "v". Then, in time t, each electron will advance by a distance $v * t$ in the direction of its velocity. So, in time t, the number of electrons that will cross a

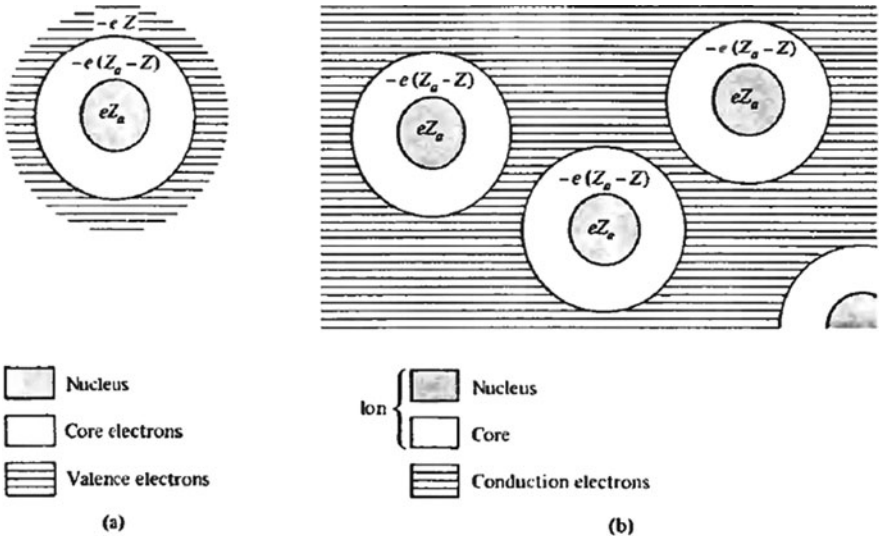


Fig. 7.2 Diagrammatic representation of free electron theory (Source: Ashcroft & Mermin, 1976)

unit area perpendicular to the direction of flow would be equal to $n^* v\ ^* t$. Since each electron carries a charge e, the total charge crossing this unit area is equal to $n\ ^*\ e\ ^*\ v\ ^* t$. Therefore, electric current (per unit area) can be expressed as

$$I = \frac{n^* e^* v^* \Delta t}{\Delta t} = n^* e^* v$$

Equation 1: Equation for Electric Current

Note that this equation indicates that the two cases of 500 electrons moving at 5 miles per hour and 5 electrons moving at 500 miles per hour will result in the same amount (or value) of electric current. That is, according to this theory, electric current is represented as a *rate* (i.e., number of electrons flowing per unit time), as well as a *quantity* that can be *conserved* under the opposing influences of *number* and *speed* of electrons.

We believe that such an approach has the following affordances. First, misconceptions researchers have shown that the constancy of electric current throughout the any linear resistive circuit is one of the most challenging phenomena for students to understand. Following Chabay and Sherwood (2000) and Haertel (1987), we argue that this can be explained using the number-speed *balancing* mechanism described above. In the circuit shown in Fig. 7.1, while there is a higher concentration of free electrons in the wire, they are moving slower due to lower voltage; whereas, in the resistor, there are fewer electrons that are moving faster toward the battery positive. This in turn can be understood in terms of inherent properties of conductors and resistors—usually a material with a higher resistance possesses a higher density of obstacles to electron flow, and/or it offers a smaller concentration of free electrons. Both effects normally appear together within a resistor and can cause a dramatic change in mobility for the electrons (Chabay & Sherwood, 2000; Haertel, 1987). Note that the generativity of this model of electrical conduction lies in the fact that the same *mechanism*—"balancing" electric current due to the simultaneous and complementary changes in the number and speed of free electrons—can explain why electric current in a series circuit remains constant throughout the circuit, even when the component wires or resistors in the circuit have different amounts of resistance.

Second, we believe that such a mechanism is *intuitive* for novices and thus can provide them with a sense-of-mechanism for understanding how electric circuits work. The construct "Sense-of-mechanism" (diSessa, 1993) can be understood as schematic knowledge structures, which, upon activation, provide learners with the following capabilities: (a) to assess the likelihood of various events based on generalizations of what does and does not happen; (b) to make predictions and post dictions; and (c) to provide causal descriptions and explanations—for example, once activated, they can justify various proportionalities that are embodied in the representation of the relevant phenomena. diSessa and colleagues (diSessa & Sherin, 1998; diSessa, 1993; Hammer, 1996) argue that a rich system of knowledge elements that are organized only to a limited degree, makes up the naïve physical sense-of-mechanism and are called phenomenological primitives or p-prims. P-prims are hypothetical knowledge structures (such as the "balancing" p-prim: *equal and opposing influences cancel each other)* and usually abstracted from common experiences (e.g., balancing with seesaws and weights).

We believe that learners' interactions with NIELS models can activate such productive and intuitive knowledge elements in their minds. For example, the effect of voltage on free electrons is represented in the NIELS models in terms of a combination of "push" and "pull"; resistance is represented in terms of "collisions" or "bouncing"; electric current is represented as a "flow" as well as a process of "filling up." Note that each of these actions (push, pull) or mechanisms (e.g., bouncing, collisions) is intuitive and can be easily understood by novices, and they have also been regarded as body syntonic (Papert, 1980). We believe that based on these simple rules, students can then (a) generate higher level mechanisms that simulate equilibration processes—such as the equality of electric current for complementary sets of values of *number* and *effective speed* of electrons toward the battery positive; and (b) explain macro-level observable phenomena such as behaviors of series and parallel circuits, how light bulbs work.

Potential Design Challenges from a Developmental Perspective

A central design challenge for the present study is posed by the differences in the prior learning experiences (primarily curricular) about *rates*, among fifth and seventh graders on one hand, and 12th graders on the other. In the middle school where NIELS was implemented, "rates" are introduced to students in the latter half of the seventh-grade academic year in their math classes. Therefore, at the time when

NIELS was introduced to them, neither fifth nor seventh-grade participants had studied rates before. On the other hand, 12th graders were already very familiar with "rates", as a part of their regular math and science curricula. This suggested that understanding electric current as the "rate" of electron flow might be easy for 12th graders, but might prove to be challenging for fifth and seventh graders.

Furthermore, previous research suggests that novices face difficulty when presented with the task of discriminating between conflicting predictions. For example, Inhelder and Piaget (1958) and Siegler (1976, 1981) documented such a stage in the development of children's understanding about the balance beam, and they also documented analogous developmental sequences in other domains (e.g., volume conservation). Let us consider a balance beam or a seesaw. If a weight is placed on each side of the fulcrum, the beam will either tilt counterclockwise, tilt clockwise, or not tilt at all. The effectiveness of a weight in causing the beam to tip is determined by the product of the weight (w) and its distance from the fulcrum (d), a construct called the *torque* associated with the weight. If the total torque associated with the weights on each side of the beam is the same, the beam will balance; otherwise, the beam will tip to the side with the greater torque. This rule has been termed in the literature as the "product-moment rule" (Hardiman, Pollatesk, & Well, 1984). Piaget found that in reasoning about this task, initially children focus only on weight of the objects placed on either end of the beam. Eventually, Piaget found that by age 14, children develop the ability to coordinate weight and distance in the balance beam problem. In fact, studies have revealed that across several experiments, only 20% of adults have produced responses to balance beam problems consistent with the product-moment rule (Jackson, 1965; Lovell, 1961; Siegler, 1976).

In a similar sense, we hypothesized that the effect of simultaneous and complementary co-variation in number and speed of electrons may be difficult for younger students (fifth and seventh graders) to understand. This is because focusing on either of the variables (instead of *both o*f them at the same time), under certain conditions, might lead to contradictory predictions. For example, while a higher number of electrons may lead to higher current, lower speed of electrons would lead to lower current. If a situation involves both these conditions occurring at the same time, then students might face challenges in making predictions. However, our goal here is to show specifically how to address this issue through redesigning the NIELS Current in a Wire model.

Lowering the Threshold for Learning: Designing NIELS to Leverage Naïve Intuition

NetLogo: A "Glass-Box" Platform for Learning and Modeling

NetLogo (Wilensky, 1999a) originated in a blend of StarLisp (Lasser & Omohundro, 1986) and Logo (Papert, 1980). From Logo, NetLogo inherits the protean "turtle." In traditional Logo, the programmer controls a single turtle, while a NetLogo model can have thousands of them. The phrase “glass-box” indicates that the underlying NetLogo code that generates each NetLogo model is always accessible to the learner, and more importantly, the NetLogo programming language is designed specifically so that novices can easily understand and modify it. From the low-threshold side, this enables novices not only to examine and modify the assumptions and rules that generate the model, but also interpret the mechanism(s) depicted in the models in terms of these simple rules of interaction between the agents that are mostly body-synctonic, instead of having to resort to the formalism of equational representations. And on the high-ceiling side, by enabling learners to modify and expand the model that they are provided with, it enables them to dive deeper into the content, as well as explore, investigate, and build models of more advanced phenomena that are typically taught in more advanced levels.

NetLogo is in widespread use in both educational and research contexts, and a variety of curricula have been embedded in the NetLogo environment. Typically, in curricula using multi-agent models (e.g., GasLab (Wilensky, 1999b), EACH (Centola, McKenzie, & Wilensky, 2000), Connected Chemistry (Steiff & Wilensky, 2003; Levy & Wilensky, 2009), BEAGLE (Rand, Novak, & Wilensky, 2007)), students begin by exploring the behavior of pre-built simulations designed to focus on some target concepts. They make predictions about the behavior of the model under varying model parameters and then test their predictions by exploring model outcomes as they manipulate variables in a simple graphical user interface. Students, however, at any time may open up the “black box” of the dynamic visualization interface and examine as well as modify the underlying rules that control the individual elements of the model. NIELS consists of several such pre-built models designed for teaching target concepts in electromagnetism. Although students can also examine and alter the NetLogo program that governs behavior of the individual agents by opening up the *procedures* window, and studies have shown that novices and young learners can indeed learn to modify and program NetLogo models (Blikstein & Wilensky, 2008; Wilensky, Hazzard, & Longenecker, 2000), participants in this study were not required to modify the underlying code.

The core of every NetLogo model is the *interface window* (see Fig. 7.3). Typically, the interface contains a *graphics window*, a *plotting window,* and several *variables* in the form of *sliders* and *buttons* that students can manipulate. It is here in the interface window that students can observe directly the interaction between the macro-level phenomenon and micro-level agents. The plotting window(s) enables students to observe the effects of their manipulations of the system on macroscopic variables, and the graphics window presents a visualization of the emergent behavior. These sources of feedback enable students to receive instant feedback about their predictions as they interact with the system by modifying system parameters. Each model also contains an *information window* that contains a description of the content underlying the model, instructions on how to use the interface window, and some suggested extensions or modifications of the NetLogo procedures.

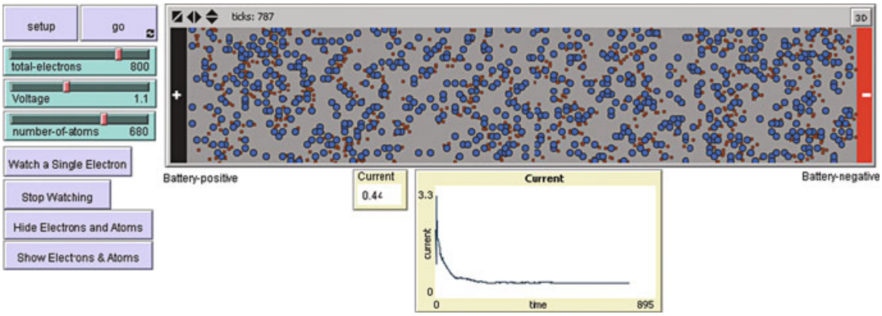


Fig. 7.3 NIELS "current in a wire" model

The Original Model: Electric Current in a Wire

This model (Sengupta & Wilensky, 2008d) illustrates how a steady electric current and resistance emerge from simple interactions between the free electrons and atoms (ionic cores) that constitute the electric circuit. It shows how the proportionality based relationships between current (I), resistance (R), and voltage (V) emerge due to the interactions between individual electrons and atoms in the wire. According to Drude's theory, in the presence of an externally applied electric field, each electron is accelerated till it suffers collisions with an atom. As a result of this collision, in our model, the electron loses its velocity and scatters, and again has to accelerate from a new initial velocity of 0, immediately after the collision.

The variables in this model are total number of free electrons *(total electrons), voltage,* and *number-of-atoms.* Additionally, students can also "watch" an individual electron, as well as "hide" the electrons and atoms from their view without affecting the underlying rules of interaction between them, so that they can focus only on the trajectories of individual electrons. The graph displayed in the model plots the instantaneous current vs. time by calculating how many electrons are arriving at the battery positive per unit time.

The Redesigned Model: Electron-Sink Model

This model, shown in Fig. 7.4, (Sengupta & Wilensky, 2008c) is a simplified, as well as modified version of the previous model. While the previous model is aimed at focusing the learner's attention on the process of movement of free electrons inside the wire, the goal of this model is to *frame* the motion of electrons in terms of a process of "Accumulation" inside the battery positive in order to help fifth and seventh graders understand the notion of electric current as a "rate" in an intuitive fashion. Based on the literature in multiplicative reasoning (Thompson, 1994; Kaput & West, 1994), our hypothesis was that such a reframing would enable students as young as fifth graders to interpret electric current in terms of *how fast*

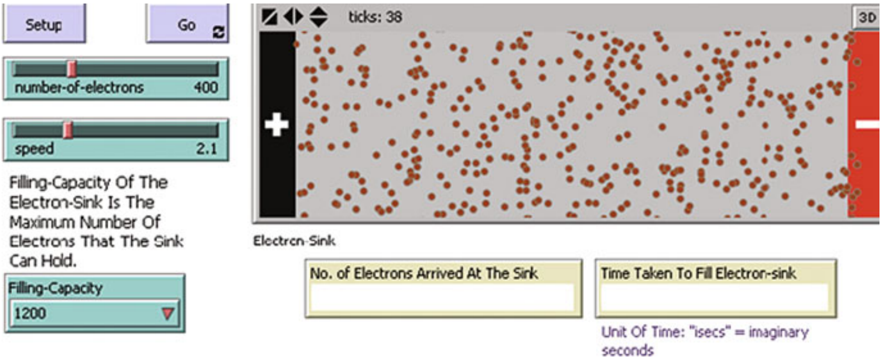


Fig. 7.4 NIELS electron-sink model

the electron-sink fills up—a qualitative and comparatively more primitive form of "rate" based understanding, which in turn can be further developed onto a more formal understanding of rate through scaffolding in successive models, as we show later.

In contrast to the Current in a Wire model, the electron-sink model therefore has only two variables: *number* and *speed* of electrons. The variables, voltage and resistance, that were present in the first model were condensed into a single variable, represented by the "speed" of electrons toward the battery positive. Another difference is that the atoms are also hidden from view. This was done so that students could focus on understanding the *effects* of the speed of electrons, as opposed focusing on the factors that *control* speed.

The battery terminals are represented as "electron-source" and "electron-sink" in the user interface of the models, as well as in the activity sheets. This was done in the hope that students would tap into the semantic schemas of the terms "source" and "sink" and use them to interpret the functions of the battery terminals. Finally, a third variable, "electron-sink capacity", was introduced into the model. The function of this variable is to stop the model once a certain number of electrons reach the battery positive, and a "monitor" (see the right-hand side in Fig. 7.2) displays the "time taken to fill the electron-sink" (T_S). In terms of situational semantics, together with the "source-sink" metaphor, this creates an overall context of "containment", in which the electron-sink can be conceived of as a reservoir or a container that in which electrons are "building up" in number.

The Study: Setting, Method, and Data

The research design is a mixed method, quasi-experimental study, including both clinical interviews and quantitative analyses. It is important to note that the comparison between groups presented here was not planned *a priori* as a controlled study. Rather, the goal of the analysis presented here is to highlight some interesting differences in terms of the learning experiences and learning outcomes among different groups of students, when each group of students used somewhat different versions of the same model. One group of students consisted of fifth and seventh graders (one section in each grade) who interacted with the NIELS Current in a Wire model (see Model B in Fig. 7.5) and is referred to here as the Pilot group. Another group consisted of fifth- and seventh-grade students (one section in each grade), who interacted with the electron-sink model, and are referred to here as the electron-sink group (see Model A in Fig. 7.5). And finally, the performances of both these groups are compared to another group of 12th-grade students who interacted with the Current In A Wire model (see Model C in Fig. 7.5). Screenshots of the user interfaces of each model are shown below in Fig. 7.5, and the differences between the models used by each group are also discussed in a following section. The activities performed by students in the different groups are shown in the Table 7.1.

It is important to note that in activity D, students in the electron-sink group were presented with a definition of electric current in terms of the activities that had just carried out—i.e., in terms of a process of accumulation of electrons inside the battery positive. In contrast, neither students in the Pilot group (fifth and seventh grade) nor 12th graders were presented with an explicit definition of electric current. Also, the process of electrical conduction depicted in the Current in a Wire model was not explicitly framed in terms of accumulation inside the battery positive. Instead, they constructed their understanding of electric current through reflecting on how each of the individual variables, such as number of electrons, voltage, and number of atoms, were related to the value of electric current.

We present two types of analysis:

(a) First, we present an analysis of explanations of students (fifth and seventh graders) who were part of the NIELS 2008 implementation and interacted with the electron-sink model. After performing the “Balancing Filling-time” activity (see activity C in the table above), students were asked to explain why they think “filling-time” was identical in both cases. The second explanation was solicited immediately after this when participants were asked to explain how they would measure electric current based on the activities they performed thus far (see activity D in the table above). The data presented here consist of (a) semi-clinical interviews conducted with participants in the electron-sink group while they were conducting the “Balancing Filling-time” task (see activity C in Table 7.1) and (b) their written responses of both the activities.
(b) In order to assess the “efficacy” of the electron-sink model, we compared the performance of students in all the groups on a particular task, in which they were asked to predict (and explain) whether electric current would be equal, higher, or lower if twice as many electrons moved twice as slowly (see activity D (Pilot Group) and activity E (electron-sink group) in the table above). The data for this task are entirely based on participant’s written responses.

During these implementations, students interacted with the NIELS models in randomly assigned groups of two or three, and the same group composition was

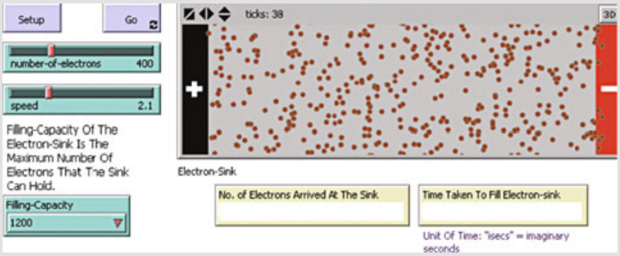
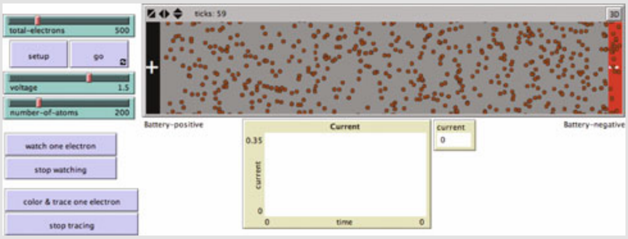
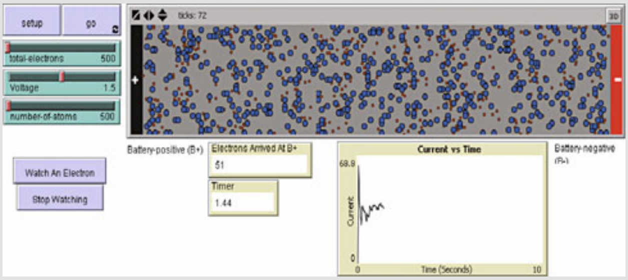
<table>
<tr><th></th><th>Model Used</th></tr>
<tr><td>Electron-Sink Group
(5th and 7th grade)</td><td>Model A: NIELS Electron-Sink Model

</td></tr>
<tr><td>Pilot group
(5th and 7th grade)</td><td>Model B: Current In a Wire (Pilot) model

</td></tr>
<tr><td>Pilot group
(12th grade)</td><td>Model C: Current In a Wire model

</td></tr>
</table>

Fig. 7.5 User interface of NIELS models used by different groups

maintained throughout the length of the implementation. Each NIELS model is accompanied by activity sheets that contain some relevant content knowledge (such as a multiple-analogy-based introduction to free-electron theory, descriptions of “variables” and other functional features of the model’s user interface) as well as instructions to guide students’ interactions with the model. Students were also required to log their observations and describe them in detail in these sheets. The activity sheets also contain frequent prompts for reflection in which students are often asked to provide detailed mechanistic reasoning of relevant phenomena. Each

Table 7.1 Learning activities performed by pilot and electron-sink groups

Pilot group	Electron-sink group
(A) Change only the value of number of electrons a. Predict how and why electric current would change. b. Observe (and compare with prediction) the effect of this alteration on electric current. *Additional activity for 12th graders only*: Draw a graph of current vs. number of electrons and identify the equation that best describes their relationship. (A list of possible equational relationships, based on proportionality, was provided to them) (B) Change only the effective speed of electrons toward the battery positive by controlling voltage, and a. Predict (and explain), the effect of this alteration on electric current. b. Observe (and compare with prediction) the effect of this alteration on electric current. *Additional activity for 12th graders only*: Draw a graph of current vs. voltage and identify the equation that best describes their relationship. (A list of possible equational relationships, based on proportionality, was provided to them.) (C) Change only the effective speed of electrons toward the battery positive by controlling number-of-atoms, and a. Predict (and explain) the effect of this alteration on electric current. b. Observe (and compare with prediction) the effect of this alteration on electric current. *Additional activity for 12th graders only*: Draw a graph of current vs. number-of-atoms and identify the equation that best describes their relationship. (A list of possible equational relationships, based on proportionality, was provided to them) (D) Explain whether electric current would be equal, higher or lower, if twice as many electrons moved twice as slowly.	(A) Change only the number of electrons a. Predict, along with mechanistic explanations how the "filling-time"(*T*) would be affected. b. Observe (and compare with prediction) how *T* is affected. (B) Change only the speed of electrons and observe how T depends on it; a. Predict, along with mechanistic explanations how *T* would be affected; b. Observe (and compare with prediction) how *T* is affected; (C) Find two widely different sets of values of number and speed for which T is identical. a. Why do you think the electron-sink filled up in the same time (*T*) in the two cases? Explain your answer in detail. (D) Given that electric current can be defined as "how fast the sink fills up," how would you measure electric current in the model? (E) Explain, if electric current would be equal, higher or lower, if twice as many electrons moved twice as slowly.

section consisted of 20 students. Note that the interventions reported in this chapter lasted one class period in each grade, and each period lasted 45 min.

The data for this study comes in two forms—semi-clinical interviews and written explanations. I conducted semi-clinical interviews with randomly selected four students in each class while they were interacting with the models. In these interviews, which were videotaped, students were asked to provide mechanistic explanations of relevant phenomena and I would often ask questions to clarify and/or disambiguate parts of their responses.

Differences Between the Models Used

There are three main differences between the electron-sink model (also referred to as model A in Fig. 7.5) on one hand, and the two versions of the Current in a Wire model (i.e., models B and C in Fig. 7.5) on the other. The first difference lies in the "framing" of motion of electrons as a process of accumulation inside the battery positive in model A. While all the models depict motion of electrons inside the wire, model A has additional constraints (e.g., maximum filling-capacity) and linguistic cues (e.g., battery positive is referred to as "electron-sink") that are specifically intended to enable learners to focus on the process of charge accumulation inside the battery positive and to conceive of electric current as *how fast* the electron-sink is filling up. The second difference among the models pertains to the representation of resistance in both the models. Note that neither model displays "atoms". Model B, however, has a variable "number of atoms", by controlling which one can alter the probability of collisions of electrons with atoms, which effectively alters the speed of each electron toward the battery positive. In model A, students control the speed of electrons toward the battery positive through the variable "speed," and there is no mention of any "mechanism" (such as collisions with atoms) through which the speed is affected. The third difference lies in the fact that electron-sink model does not display the value of electric current or the current vs. time graph, whereas both of these are present in models B and C.

There is also one difference between models B and C. While both these models involve collisions between electrons and atoms as the "mechanism" of resistance, in model C, the atoms that act as hindrances to the electrons are visible to the learner, and the resistance can be controlled by controlling the number of atoms. In model B, the atoms are not visible to the learner; instead by controlling the number-of-atoms, they can control the probability of electrons experiencing collisions as they move toward the battery positive. Note that the learning activities performed by the pilot group students (who interacted with model B) and the 12th graders (who interacted with model C), as listed in Table 7.1, do not leverage this difference between the models, and we therefore believe that this does not present any significant confound to the study reported in this chapter.

Coding and Analysis

Throughout the studies reported here, we use the following "constructs" in order to classify learners' knowledge: registrations, causal schemas, and phenomenological primitives or p-prims.

Registration

As stated in Sengupta (2009), and building on Roschelle (1991) and Lee and Sherin (2006), we define registrations as the representational structures embodied in the user interface of the NIELS models that are made selectively salient and potentially meaningful during the course of an interpretive action by the learner. Registrations, in the sense we use it in this chapter, indicate how learners parse the phenomena represented in the models through focusing on certain model attributes that are salient to them. Typically, registrations were identified in participants' responses to the following interview questions: "what's going on in the model?" or "can you explain to me what you are currently doing?" Similarly, in the activity sheets, participants were often asked to describe what they were observing in the model as a result of changing particular variables in the model, or for particular configurations of the model's variables.

For example, if the movement of electrons register in the learners' minds as a process of *accumulation* inside the battery positive, learners can then be prompted to think about in the factors on which rate at which the electron-sink is filling up depends on—i.e., both the number and speed of electrons. Learners can then be prompted to think about electric current as how fast the battery positive is filling up with electrons.

Causal Schema

Following Forbus and Gentner (1986), we define causal schemas as binary relations among variables. It is a weak form of a concept—i.e., the mechanisms represented in causal schemas are often not elaborated. However, the coordination of several different causal schemas can lead to a more detailed explanation or interpretation of a "mechanism" or a "process."

Causal schemas were identified based on learners' written or verbal explanations when participants would often be asked to explain the effect of changing particular variables. An example of a casual schema pertaining to the electron-sink model is "higher speed [of electrons inside the wire] leads to a lower value of the "filling-time." Here, "higher speed" is the causal agent, and "lower filling-time" is the result, and in such cases, the coding as performed by identifying the relevant causal agents and relationships between them in students' written or verbal responses.

Phenomenological Primitives

P-prims or phenomenological primitives are hypothetical knowledge structures that are abstracted form our early experiences with the physical world. These are more "generalized" and "abstract" than causal schemas (which are rather situation-specific), and are activated upon being recognized due to familiar contextual cues. An example of a p-prim particularly relevant to this study is cancelling (diSessa, 1993). diSessa points out that this p-prim is activated in situations in which two opposing forces "try" to achieve mutually exclusive results but happen to cancel each other out. diSessa (1993) writes: "Canceling is likely a common abstraction for many cases of joint, although not necessarily simultaneous, application of "equal and opposite" tendencies. For a situation involving dynamic balancing, canceling justifies lack of result" (diSessa, 1993, p. 135).

Note that the important difference between causal schemas and p-prims is that causal schemas are more directly model-based, whereas p-prims are comparatively more abstract hypothetical knowledge structures. For example, the "blockage" causal schema expresses a relationship between a higher number of atoms and the difficulty of movement of electrons—i.e., more blockage means more travel time for electrons. This is model-based, as it directly expresses a relationship between two entities in the model. On the other hand, the dynamic balance p-prim is comparatively more abstract, in the sense that is domain general—diSessa (1993) argue that this p-prim can be applied to explain several situations across domains that involve the action of two opposing forces or directed influences.

Findings

Mental Models of Students in the Electron-Sink Group (Fifth and Seventh Grade): Understanding Conservation of "Filling-Time"

The data for this section comes from interviews with four students in each grade in the electron-sink group, as they were interacting with the model and performing activity C mentioned in Table 7.1. As scaffolded by the sequence of activities A and B as listed in section Table 7.1, students typically started out by observing how number and speed of electrons, when varied separately, affect the value of "filling-time" (i.e., how long it takes for the sink to fill up). I present here the analysis of two sample interviews that are representative of the entire corpus of eight. Of these, one interview is with a fifth-grade student and the other is with a seventh grader. These interviews reveal how a particular type of *registration*—i.e., students' mental construal of charge flow as a *building-up process* inside the battery terminal enabled them to identify a mechanism (e.g., compensation, or balancing) through which both the number and speed of electrons simultaneously affect electric current. These interviews, as evidenced in the sections below, then bring to light how students come to coordinate the number- and speed-based causal schemas in order to explain how the value of filling-time can be conserved, through using the "dynamic balance" or "cancelling" p-prim.

Amber (fifth grade)

This excerpt indicates that the student Amber was able to identify that the filling-time (T) is inversely proportional to the speed of the electrons. In lines 2 and 4, she explained that her "theory" was that as electrons have higher speed, more of them get into the battery positive and occupy more and more room, which thereby reduces the filing time. Lines 4 and 6, however, also indicate that the learner was changing

Excerpt 1:

Interviewer (Int): *So what is going on in this model?*

1. AMBER: *when you increase the speed, ummm.. more negatives go to the positive umm.. and probably make more electricity*
2. Int: *And the time (pointing to the monitor displaying T_s on the computer screen)..? what happens to the time?*
3. AMBER: *well.. the time goes down.. I have a theory that since it (electrons) is going so fast, it takes up more and more room (inside the electron-sink).*
4. Int: *since "it" is going so fast? (urging Amber to continue her explanation)*
5. AMBER: *since it is going so fast, it takes up more and more room and so less time to fill it up (points to the electron-sink on the screen)*

her spatial perspective from being inside the wire to being inside the electron-sink. For example, the phrase "it is going so fast" in line 5 refers to an electron moving inside the wire, while the phrase "it takes up more and more room" in line 6 refers to how the electrons are filling up the electron-sink by occupying incrementally more "room" inside the battery terminal. So, the motion of electrons, once they enter the positive terminal, registered in the student's mind as a form of *accumulation* (i.e., a *building-up* process).

In the following excerpt, Amber explains how she got the value of T to be equal for two different sets of values of the number and speed of electrons.

Excerpt 2:

1. Int: *so can you explain how you did the value of time to be equal in both cases?*
2. AMBER: *what do you mean?*
3. Int: *I mean... the number (of electrons) here increased, and the speed decreased, right?*
4. AMBER: *right..*
5. Int: *but you still get the same time, right?*
6. AMBER: *right*
7. Int: *how is that happening?*
8. AMBER: *well because you are taking off the 800 to get 500, and because you are taking off from one number, then you have to add to another number.. like 4 + 3.. if you take 2 out of 4, then you have to put that two back on to 3... so it would be 2 + 5, and that would be the same thing as 4 + 3... so that is what basically what we did...*
9. Int: *OK.. so that was a really nice explanation.. so could you explain that in terms of the wire and the electrons?*
10. AMBER: *So.. umm.. for the electrons.. you had to decrease their number, and umm.. the speed.... umm.. you had to increase, to make up for the time...*

Amber's explanation here is based on the following: (a) causal schemas that involve *number* and *speed* of electrons as individual causal agents, individually affecting the value of T; and (b) a coordination of these causal schemas, i.e., *simultaneous* and *mutually compensatory* change in both the number of electrons and their speed, that can conserve of the value of T. Amber's observations (as a part of activities A and B as shown in Table 7.1), in the form of written responses, indicate that she was able to identify that number and speed, when varied individually, affected how fast the sink was filling up. In line 8, she explains how by changing both these causal agents, when simultaneously, results in keeping the value of the filling-time (T) unchanged. To do so, she uses the following metaphor: in order to keep the sum (S) of the two numbers (A and B) constant, if one of the numbers is increased by a certain amount (x), then the other number must be decreased by the same amount (x). That is,

$$S = A + B = (A + x) + (B - x).$$

I argue that Amber's explanation is based on a model of "compensatory equivalence." That is, if two causal agents act together to produce a result, then the result can be kept unchanged by altering the effect of both the agents in a mutually compensatory fashion. In this case, the "filling-time" is the result that remains unchanged when the values of both the causal agents (i.e., number and speed) are altered in a mutually compensatory way. This is reflected in line 10, when Amber explains that *you had to decrease their number, and umm.. the speed.... umm.. you had to increase, to make up for the time...*

One could further argue that this explanation is an evidence of the "cancelling" p-prim (diSessa, 1993). diSessa points out that this p-prim is activated in situations in which two opposing forces "try" to achieve mutually exclusive results but happen to cancel each other out. And, "for a situation involving *dynamic balancing, cancelling* justifies lack of result" (diSessa, 1993, p 135). In this case, we believe that the equal and opposite tendencies of the *higher number* and *lower speed* of electrons (or vice versa), in terms of their effects on the filling-time, result in a dynamic balance scenario, which in turn activates the "cancelling" p-prim.

David (and Sam) (seventh Grade)

The following interview took place when David was performing the balancing time activity. I asked David to explain how they were planning to approach the task, and the following conversation ensued:

Excerpt 1

(1) I: so how are you guys working on number 14? What is the idea?
(2) David: So we are trying to get the speed.. trying to change the speed.. trying to variate.. kind of variate what the speed is coz we want to make it (pointing to Ts on the Activity Sheet) almost equal or close to 216 isecs, because in question 5, that is what the speed (Ts) is...
(3) I: So are you variating.. like increasing and decreasing the speed?
(4) David: Yeah..
(5) Sam (to David): well 2.6 is going to be too fast
(6) I: so can you tell me if the speed is going to be higher or lower?
(7) Sam: We just got it.. it is 2.4..
(8) David: Its (Ts) the exact same
(9) Sam: Yeah.. we were able to get the exact same (Ts)

(10) David (to me): The speed was higher because the number of electrons that were capable of being able to go in to the positive charge at one time was lower

David's response in line 10 indicates that the situation at hand registered in his mind as one in which electrons are "going into" the battery positive. It indicates a process of simultaneous "entry" of multiple electrons (*going into, at one time*), which we argue, in David's mind, plays an important role in determining how fast the electron-sink is filling up. David's written explanation quoted below provides a clearer picture of his mental model of the relationship between "filling-time" and the process of *simultaneous entry* of electrons:

> The filling-time is lower when many electrons go in at the same time, so they fill up quickly. The time is the same if there are more electrons moving with less speed and less electrons but moving faster

Figure 7.6 below is a representation of David's mental model of "filling-time".

Each "Time-event", as indicated in Fig. 7.6, represents a unit of time, during which a certain number of electrons enter the electron-sink. The notion of a time-event is evidenced in David's statement in line 10 in the above excerpt, where he explicitly mentions that a certain number of electrons "go in at one time." His explanation therefore indicates that the constituents of "filling-time" are a series of these repeated, discrete time-events, each of which involves *simultaneous entry* of multiple electrons. According to this model, if more electrons are capable of going in "at one time," the filling-time is lower, and vice-versa.

Furthermore, David's written explanation and interview excerpt also indicated that he was able to identify the mutually compensatory role of number and speed of electrons that resulted in conserving the value of filling-time. His interview response (see line 10 in Excerpt 1) indicated that a higher speed can compensate for a lower number of electrons, as it enables more electrons to "go in to the positive charge at one time". And in his written response, he identified that the filling-time is the same if "if there are more electrons moving with less speed, and less electrons but

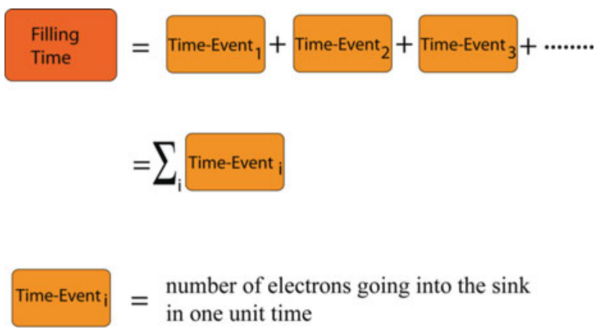


Fig. 7.6 David's mental model of "filling-time"

moving faster." We therefore believe that David's responses indicate a dynamic balance schema, in which the number and speed of electrons act as opposing influences that result in keeping the value of filling-time unchanged. As discussed earlier in the previous cases, we believe that this is also an evidence of the "canceling" p-prim.

Written Explanations of the "Balancing Filling-Time" Activity

As indicated in Table 7.1, after performing the "Balancing Filling-time" activity, students were asked to explain why the electron-sink filled up in the same time (*T*) in both cases. Students' responses to this question were coded into the following types: number-speed complementarity, filling-capacity-based, and speed-based. Sample responses, along with percentages of responses of each type, are shown in Table 7.2.

Responses that included a mutually complementary or compensatory change in both number and speed of electrons were coded as Number-Speed Complementarity. It is notable that responses of the majority of the students in each grade (70% in fifth grade and 75% in seventh grade) were of this type. Speed-based responses indicated that the alteration in speed was the reason why the value of time was identical in both cases. Responses of 5% of students in each grade belonged to this category. Finally, responses that were coded as "Filling-capacity-based" indicated that the filling-time was identical in both cases as the same number of electrons (equal to the filling-capacity of the electron-sink) came into the battery positive. Fifteen percentage of fifth graders' responses and 10% of seventh graders' responses belonged to this

Table 7.2 Students' responses—"balancing time" activity

Type of explanation	Sample response	% of students (fifth grade)	% of students (seventh grade)
Number-speed complementarity	"Speed goes up and number goes down to keep time same"; "Number and speed balance each other out"; "With less speed and more electrons, more electrons get in. But with more speed and less electrons, the speed pushes more electrons."	70	75
Filling-capacity-based	"Same amount of electrons come in in both cases"; "Because same number of electrons come in and fill up the sink"	15	10
Speed-based	"speed went up"; "speed was higher"	5	5
No response	–	10	15

category. Ten percentage of students in fifth grade and 15% of students in seventh grade did not respond to the question.

From "Filling-Time" to Electric Current

This section focuses on how fifth and seventh graders in the electron-sink group related their understanding of "filling-time" to the notion of electric current. The data for this section come from students' written responses in the activity sheet, pertaining to activity D in Table 7.1 After completing the activity of balancing the value of filling-time discussed in the previous section, students in the electron-sink group were asked to perform the following activity:

> Together, the wire and the battery terminals shown in the computer model are called an *electric circuit.* Electric current in any circuit can be understood as *how fast the electron-sink (i.e., the battery positive) is filling up.* Based on all the activities you have done so far, how would you measure electric current (i.e., how fast the electron-sink is filling up) in the circuit shown in the computer model?

Students' responses were coded as follows: number based, speed based, time based, number-and-speed based, number-and-time based. Figure 7.7 shows the percentage of responses of each type of students in both fifth and seventh grades, and Table 7.3 shows sample responses pertaining to each type.

Responses were coded in terms of what model attributes students indicated had to be measured in order to measure electric current in the circuit shown in the model. *Number-based* responses typically indicated "number of electrons" as the only attribute that would have to be measured in order to measure electric current.

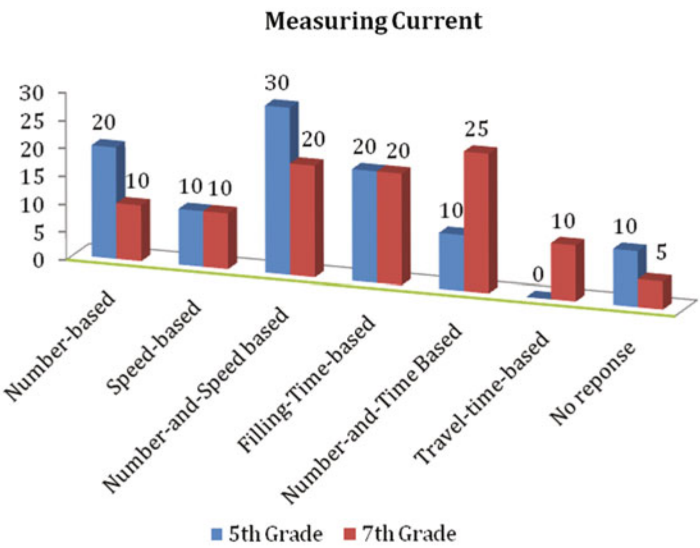


Fig. 7.7 Percentage of different types of students' reponses to the "measuring current" activity

Table 7.3 Students' responses—"measuring current" activity

Type of responses	Sample responses	% of students (fifth grade)	% of students (seventh grade)
Number-based	"I will count how many electrons are there in the circuit" "If there are more electrons there will be more current"	20	10
Speed-based	"You can measure current by the speed slider" "speed of electrons"	10	10
Number-and-speed based	"I would count how many there are and how fast they are moving" "Both number and speed of electrons"	30	20
Filling-time based	"how long it takes to fill the sink" "Count *T*"	20	20
Number-and-time based	"I would measure how many are coming in and in what time" "number and *T*"	10	10
Travel time based	"I would measure how long the ticks (electrons) take to reach the positive"	0	10
No response	–	10	5

Twenty percentage of fifth graders and 10% of seventh graders' responses were of this type. Similarly, responses that were coded as *Speed-based* typically indicated the "speed of electrons" or "how fast electrons are going" as the only attribute to be measured, and responses of 10% of students in both fifth and seventh grades were of this type. *Filling-time*-based responses indicated that electric current could be measured by "counting" or "measuring" the value of *T* (or "how long it takes to fill the sink). Twenty percentage of students' responses in each grade were of this category.

Note that 30% of fifth graders and 20% of seventh graders mentioned both number and speed of electrons as attributes that would have to be measured in order to measure electric current. These responses were coded as *number-and-speed* based. Students whose responses were coded as *Number-and-time based* indicated that they would measure electric current in the circuit by calculating how many electrons are inside the sink and dividing it by the time. This suggests that some students were constructing an understanding of electric current as a particular ratio of number of electrons in the sink and time. 10% of fifth graders' and 25% of seventh graders' responses were of this type.

Students whose responses were coded as *travel time* based, indicated that they would calculate how much time the electrons take to reach the battery positive in order to measure electric current. Only 10% of seventh graders' responses were of this type.

These responses indicate that even when more than 80% of the students in each class successfully performed the "Balancing time" activity, only 30% of fiftth graders and 20% of seventh graders indicated that electric current could be measured by observing or calculating both the number and speed of electrons. One possible explanation is as follows: factors or attributes that affect electric current, in the students' minds, are not always isomorphic to the factors or attributes that need to be measured in order to measure electric current.

Note that the *total* percentage of students whose responses were either coded as "Filling-time based" or "Number and speed based" or "number and time based" was 60% in fifth grade and 65% in seventh grade. It is noteworthy that these responses focus on model attributes (or variables) that either explicitly involve number and speed of electrons, or are directly affected by both of them. Therefore, this indicates that majority of the students were able to develop an understanding of electric current based on the effects of both the number and the speed of electrons.

Between-Group Quantitative Comparisons of Post-explanations of "Balancing Current"

Note that after their interaction with the models, participants in both the groups were asked to predict whether electric current would be higher if twice as many electrons moved twice as slowly and select an explanation from a list to justify their selection. Specifically, they were asked to answer the following question:

Q 1: In Wire A, there are 400 electrons and the speed of the electrons is 40 units. In another wire (Wire B), there are 800 electrons and the speed is 20 units. Which of the following do you think is true:

(a) Electric current in Wire A is more than in Wire B
(b) Electric current in Wire B is more than in Wire A
(c) Electric current is same in both Wire A and Wire B.

Q 2: Now, from the list below, select the option(s) that describe(s) the reasons for your choice (NOTE: You CAN select more than one option)

(a) Current is higher in Wire B because there are more electrons in Wire B
(b) Current is lower in Wire B because the speed of electrons is lower in Wire B
(c) Current is lower in Wire A because there are less electrons in Wire A
(d) Current is higher in Wire A because the speed of electrons is higher in Wire A
(e) In Wire B, there are more electrons with less speed and in Wire A, less electrons with more speed. So they have equal current."

Our analysis reveals that majority of the fifth- and seventh-grade participants in the pilot group were unable to predict (and explain) the correct behavior. In their responses to Q 2, 45% of the students in fifth grade and 50% of students in seventh grade selected either option (a) or (c), indicating the current would be higher when there are more electrons (or lower when there are fewer electrons). Fifty five percent of the students in fifth grade and 44% of seventh graders indicated that current would be higher when the electrons are moving faster (or, lower when the electrons are moving slower). Only 5% of the seventh graders in the pilot group, and 5% of the students in fifth grade selected option (e), indicating that the number and speed of electrons when altered together in a complementary fashion, that ensures the constancy of electric current. On the other hand, 90% of the 12th graders were able to make the correct prediction and identify the compensatory relationship between number and speed of electrons as the cause.

In contrast, 92% of fifth grade and 94% of seventh-grade students in the Electron-sink group identified option (e) to indicate their reasoning. This indicates that students were able to identify compensatory effects of *number* and *speed* of electrons on electric current. These results are shown in Figs. 7.8 and 7.9.

Responses of fifth and seventh graders in the electron-sink group were compared to that of 12th graders in the pilot group using one-way ANOVA (F (2, 58) = 0.5241

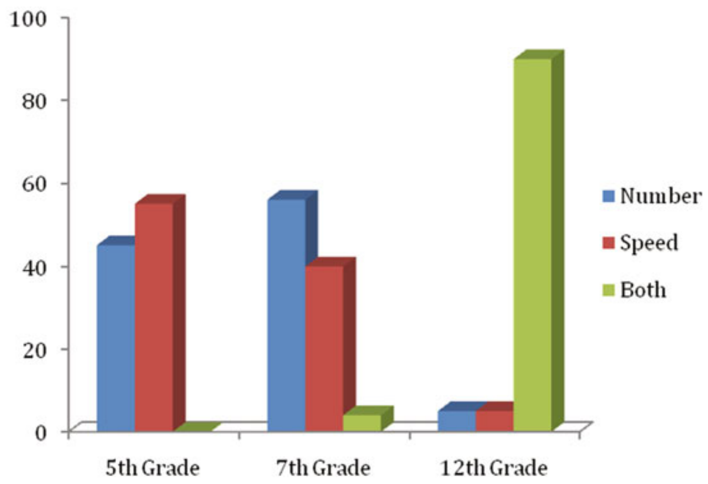


Fig. 7.8 "Balancing" current: A comparison of pilot group and 12th grade responses

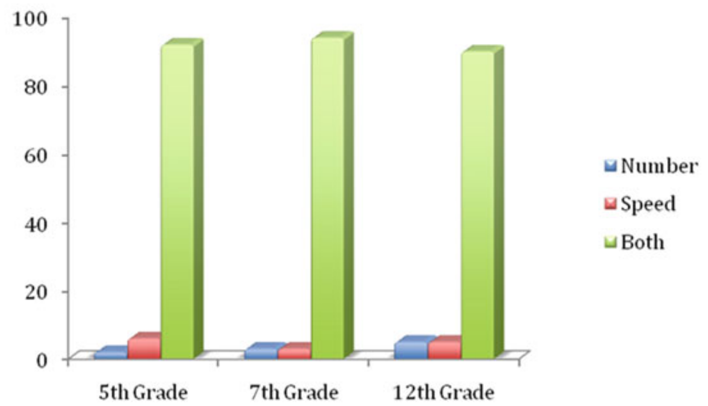


Fig. 7.9 "Balancing" current: A comparison of electron-sink group and 12th grade responses

($p > 0.5$)), indicating that there is no significant difference in mean performance between these groups. In other words, the performance of fifth and seveth graders in the electron-sink group is indeed comparable to that of the 12th graders in the pilot group.

Discussion

From the epistemological perspective, the central goal of this chapter was to highlight the epistemic significance of a particular design strategy—framing electrical conduction as a process of accumulation of charges inside the battery positive terminal, using a multi-agent-based approach. Overall, the results reported here suggest that this design strategy was indeed successful, as indicated by the explanations of 5th and 7th graders in the electron-sink group reported in the section "Findings".

Three points are noteworthy in this respect. The first point concerns our proposed theoretical model for analyzing misconceptions in electricity, where we argued that the same naïve knowledge resources that have been found to be responsible for generating misconceptions, can be bootstrapped at the microscopic level to engender a correct and deep understanding of the same phenomena. This corroborates our claim that misconceptions in electricity can indeed be understood as behavioral evidences of "slippage between levels" (Sengupta & Wilensky, 2009). For example, earlier in this chapter, we have pointed out that several researchers have observed that novice students often use the "source-sink" model in reasoning about the behavior of electric current in a circuit, and this leads to erroneous predictions that have been noted as "misconceptions". Note that as Reiner et al. (2000) points out, typically, such responses are limited to the macroscopic-level descriptions of the relevant phenomenon. The analysis presented in this chapter suggests that the same source-sink model, when appropriated to describe the behavior of microscopic level objects (agents) such as electrons (instead of electric current, the macro- or aggregate-level phenomenon) can indeed act as a productive epistemic resource for students. It enables them to focus on how fast the sink is filling up, and thereby develop an understanding of the conservation of the "filling-time" (and hence, electric current), based on simultaneous and compensatory changes in the values of number and speed of electrons. The learners are thus able to construct conceptual links between the micro-level agents and their attributes on one hand, and the macro-level phenomena on the other. This was evident in both the interview responses of the students (which highlight their emergent mental models), as well as their written responses. This is particularly significant, as Eylon and Ganiel (1990) argued that the missing macro-micro link is at the root of students' difficulties in the domain of electromagnetism.

Furthermore, this chapter shows that our design strategy enabled learners as young as fifth graders to develop an understanding of electric current as a "rate" of electron flow by bootstrapping their intuitive knowledge of "building up" (Thompson, 1994). This leads us to our second point: The ability to bootstrap learners' repertoire of intuitive knowledge is a particularly important affordance of multi-agent-based models, and this strategy has been shown to be effective in alleviating misconceptions of novice learners across several domains: chemistry (Stieff & Wilensky, 2003; Levy & Wilensky, 2005), biology (Reisman & Wilensky, 2006), materials science (Blikstein & Wilensky, 2009), physics (Sengupta & Wilensky, 2009, under review; Wilensky, 2003), etc. In this perspective, misconceptions are not resultant from naïve intuitive knowledge that is incompatible with expert ontology; rather, as our work shows, a deep understanding can indeed emerge through bootstrapping naïve intuitive knowledge.

Our third point relates to what Wilensky (2006) and Wilensky and Papert (in progress) termed "restructurations." Wilensky and colleagues defined "structuration" as the way (i.e., the representational infrastructure) in which knowledge is encoded in a discipline. Re-structuration means altering this encoding by changing the representational infrastructure. Wilensky and colleagues argued that when the representational infrastructure in a domain is altered in such a way that it aligns with intuitive knowledge structures of novices, it leverages the "learnability" of the domain. An example of restructuration is the representational system of multi-agent-based models—specifically the NetLogo platform—which enabled us to create a suite of models that are well aligned with naïve intuition, and allowed us to implement our specific design strategy of framing electric current as a process of accumulation. The results reported here enabled much younger students (fifth graders) to develop a deep understanding of electric current. Wilensky (2003) provides another example in which emergent multi-agent computational (NetLogo based) representations enabled middle school students to learn statistical mechanics, which is traditionally taught using equation-based representations in advanced physics courses (college level and beyond). Other examples can be found in Blikstein and Wilensky (2006), where the authors show how NetLogo-based representations can enable novices to engender an expert-like understanding of key concepts in materials science. Even earlier examples of restructurations that extend beyond physics include Papert and his colleagues' research on fifth graders learning fractions using Logo (Harel & Papert, 1991) and Wilensky and Reisman's (1998 (2006)) research on restucturating biology using NetLogo models, etc. Each of these studies showed that bootstrapping novices' agent level instuitions can leverage learnability in the domains of physics, mathematics, materials science, and biology. In other words, the new structurations (i.e., computational representations embodied in the designed learning environments) were much more closely aligned with the novices' intuitive knowledge than the corresponding traditional structurations (e.g., equations and other mathematical formalisms) that are difficult for these novices to understand.

Finally, it is noteworthy that our work presented here raises an interesting question: if fifth graders can now learn more advanced content as shown in this chapter, then "what happens next"? That is, what happens when these students advance to higher grades (6th–12th)? Answering this question requires an inherently developmental perspective, as our colleagues Lehrer and Schauble (2006) have argued for. The present chapter focuses on how the same model can be successfully adapted for 12th and 5th graders through *reframing* the same emergent phenomenon (flow vs. accumulation), thus lowering the learning threshold. Note that on the "high-ceiling" side of the spectrum, although 12th graders in this study performed additional activities such as conducting experiments with the variables in the model, this was not discussed in this chapter; furthermore, we consider this to be only a preliminary exploration of the "high-ceiling" side of this spectrum. Answering this important question is an important component of our current research agenda, and we believe that developing a longer term learning progression will undoubtedly have significant implications for both researchers in Learning Sciences and for the National Science Education Standards.

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Chapter 8
Engineering-Based Modelling Experiences in the Elementary and Middle Classroom

Lyn D. English and Nicholas G. Mousoulides

Introduction

A new and increasingly important field of research in the elementary and middle school curriculum is engineering education. Researchers in mathematics, science, technology, and engineering education are exploring innovative ways to introduce younger students to the world of engineering (e.g. Capobianco & Tyrie, 2009; Cunninghman & Hester, 2007; Lambert, Diefes-Dux, Beck, Duncan, & Oware, 2007; Mousoulides & English, 2009; Zawojewski, Diefes-Dux, & Bowman, 2008). The increasing complexity, interconnectivity, technology dependence, and competitiveness in our world present new challenges for individuals and nations, challenges that cannot be met "by continuing education as usual" (Katehi, Pearson, & Feder, 2009, p. 49).

The recent focus on engineering education in schools has been fuelled by the concerns of several nations that the demand for skilled workers in mathematics, science, engineering, and technology is increasing rapidly yet supply is declining. For example, the number of graduating engineers from U.S. institutions has slipped 20% in recent years (National Academy of Sciences, 2007; OECD, 2006), while in Australia, the number of engineering graduates per million lags behind many other OECD countries (Taylor, 2008). To complicate matters, recent data reveal waning student interest in engineering, poor educational preparedness, a lack of diverse representation, and low persistence of current and future engineering students (Dawes & Rasmussen, 2007; Lambert et al., 2007). It is thus imperative that we foster an interest and drive to participate in engineering from an early age. To date, there has been very limited research on integrating engineering experiences within the elementary and middle school curricula.

This chapter reports on one study that is attempting to address such integration. We first briefly consider emerging links between engineering, science, and technology education, then focus on engineering education for young learners. One

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_8,

approach here, a models and modelling perspective, is explored next. To illustrate this perspective, an engineering model-eliciting activity, the *Water Shortage Problem*, is examined. Principles for designing model-eliciting activities follow. The remainder of the chapter explores a study in which two classes of 11-year-old students independently worked, in groups, the *Water Shortage Problem*. Of particular interest here were the nature of the models the students developed and how these models evolved during the course of the activity.

Engineering, Science, Mathematics, and Technology Education

Given that engineering education as addressed here represents one approach to integrating engineering-based experiences within the curricula, it is worth noting briefly some pertinent recent developments in technology and science education. The inquiry and design processes that are being embraced by these subjects parallel those of engineering. For example, the new design focus of the USA technology education standards (International Technology Education Association, 2000) aligns the subject more closely towards engineering, which means the links with students' science and mathematics learning are imperative (Lewis, 2006; Sidawi, 2009; Wicklein, 2006). As Lewis pointed out, some states in the USA (e.g. Wisconsin and Utah) have developed joint science and technology/engineering curriculum frameworks. In doing so, the technology subject has been refocused towards engineering, embodying the methodology of the engineer. Likewise, science education, with its emphasis on inquiry, adopts the methodological approach of the scientist. Within the science education community, design is being seen increasingly as a pathway to students' scientific understanding (e.g. Kolodner, 2002; Sidawi, 2009). In the engineering-based modelling experiences of the type we address here, design, in the form of four iterative processes (addressed later), is seen as central to students' model development. Indeed, models and modelling, of which there are many interpretations and forms, may be seen as a strong foundation for linking science, technology, mathematics, and engineering (Gilbert, Boulter, & Elmer, 2000).

Engineering Education for Young Learners

Engineering education in the elementary/middle school aims to help students understand and appreciate the problems engineers face, how engineering shapes the world utilizing important ideas from mathematics and science, and how it contextualizes mathematics and science principles (Dawes & Rasmussen, 2007; Katehi et al., 2009). Engineering-based experiences encourage students to generate effective tools for dealing with our increasingly complex, dynamic, and powerful systems of information (Zawojewski, Hjalmarson, Bowman, & Lesh, 2008). The experiences build on children's curiosity about the scientific world, how it functions, and how we interact with the environment, as well as on children's intrinsic interest in designing, building, and dismantling objects in learning how they work (Petroski, 2003).

Researchers in engineering education are posing a number of core questions in need of attention, including "What constitutes engineering thinking for elementary school children?", "How can the nature of engineering and engineering practice be made visible to young learners?", and "How can we integrate engineering experiences within existing school curricula?" (Cunningham & Hester, 2007; Dawes & Rasmussen, 2007; Katehi et al., 2009).

Recent literature has reported on a number of approaches to addressing these issues. These include the *Engineering Is Elementary* program at the National Center for Technological Literacy at the Museum of Science in Boston (Cunningham & Hester, 2007), where there is a focus on the professional development of teachers, the development of students' awareness of engineering in society, and students' facility in applying an engineering design process in solving real-world, engineering-based problems.

In a similar vein, The Institute for P-12 Engineering Research and Learning (INSPIRE, Strobel, 2009) conducts teacher professional development research, assessment research, and student learning research. A core focus of this research is the development and implementation of model-eliciting activities, which has received limited attention in engineering education research. We have adopted this modelling approach in introducing engineering-based experiences in elementary and middle schools in Cyprus (e.g. Mousoulides & English, 2009).

A Models and Modelling Perspective for Engineering Education

Model-eliciting activities are derived from a *models and modelling perspective* on problem solving in mathematics, science, and engineering education and provide students with a future-oriented approach to learning (Diefes-Dux & Duncan, 2007; English, 2010; Mousoulides & English, 2011; Hamilton, Lesh, Lester, & Brilleslyper, 2008; Lesh & Doerr, 2003; Lesh & Zawojewski, 2007). Students are presented with authentic engineering situations (referred to here as *Engineering Model-Eliciting Activities*) in which they repeatedly express, test, and refine or revise their current ways of thinking as they endeavour to generate a structurally significant product—that is, a model comprising conceptual structures for solving the given problem. The activities give students the opportunity to create, apply, and adapt mathematical and scientific concepts in interpreting, explaining, and predicting the behaviour of real-world-based engineering problems.

Working in small groups, students are presented with complex data that have to be interpreted, differentiated, prioritized, and coordinated to produce a solution model. In doing so, students elicit their own mathematics and science concepts, in contrast to relying on the teacher or textbook for the required content. Furthermore, the mathematics and science content students experience in working these activities differs from what is taught traditionally in the curriculum for their grade level, because different types of quantities and operations are needed to deal with realistic situations. For example, the types of quantities needed in realistic mathematical situations include accumulations, probabilities, frequencies, ranks, and vectors, while the operations needed include sorting, organizing, selecting, quantifying, weighting, and transforming large data sets (Doerr & English, 2003; Lesh, Zawojewski, & Carmona, 2003). Modelling problems thus offer richer learning experiences than the standard classroom problem-solving tasks. For example, in the typical mathematical "word" problems, students generally engage in a one- or two-step process of mapping problem information onto arithmetic quantities and operations. In most cases, the problem information has already been "de-contextualized" and carefully mathematized for the students. Their goal is to unmask the mathematics by mapping the problem information in such a way as to produce an answer using familiar quantities and basic operations. These traditional word problems restrict problem-solving contexts to those that often artificially house and highlight the relevant concept (Hamilton, 2007). They thus preclude students from creating their own mathematical constructs.

Research has shown that students progress through four key iterative processes as they develop their models in working model-eliciting activities (Lesh & Zawojewski, 2007), namely: (a) Understanding the context of the problem and the system to be modelled, (b) Expressing/testing/revising a working model, (c) Evaluating the model under conditions of its intended application, and (d) Documenting the model throughout the development process. The cyclic process is repeated until the idea (model or design) meets the constraints specified by the problem (Zawojewski et al., 2008). These key iterative activities are illustrated in Fig. 8.1 (Diefes-Dux, Osburn, Capoobianco, & Wood, 2008).

Model-eliciting activities facilitate students' creation of a variety of interacting representational media for expressing and documenting their models, including computer-based graphics, tables, lists, paper-based diagrams and graphs, and oral and written communication (Lesh & Harel, 2003). Because these representations embody the factors, relationships, and operations that students considered important in creating their models, powerful insights can be gained into the growth of their mathematical and scientific thinking.

An Engineering Model-Eliciting Activity

The engineering-based problems we have implemented in elementary and middle school classrooms are realistic, open-ended problems where a client requires a team of workers to generate a product (a model) for solving the given problem. The model is to identify a process that the client can use to solve not only the given problem, but also similar problems. We provide an example here of an environmental engineering problem, namely, the *Water Shortage Problem* (presented in the Appendix), developed by the authors.

In the *Water Shortage Problem* students are sent a letter from a client, the Ministry of Transportation, who needs a means of (model for) selecting a country that can supply Cyprus with water during the next summer period. The letter asks students to develop such a model using the data provided, as well as search

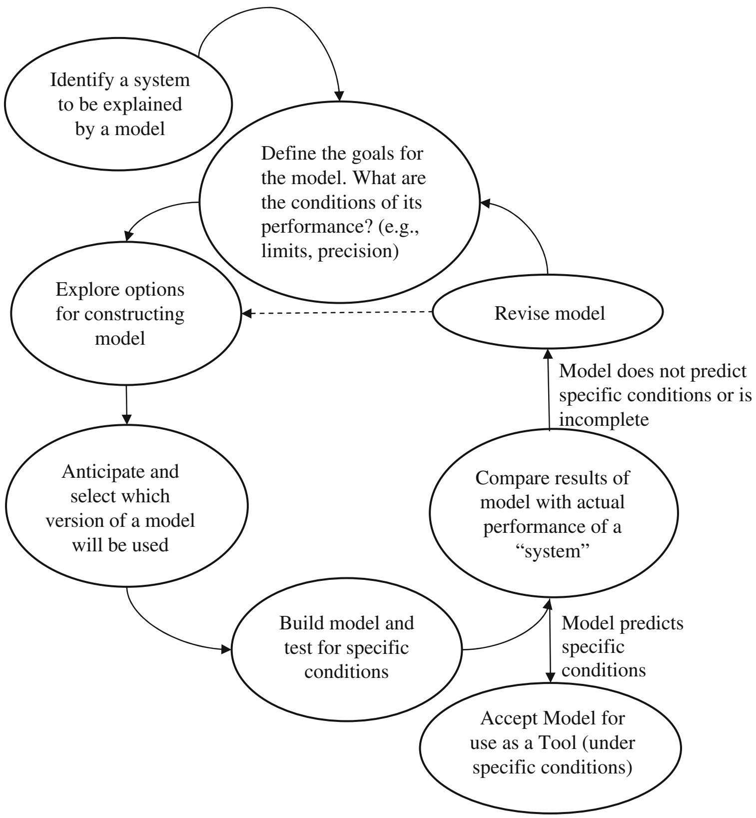

Fig. 8.1 A models and modelling approach to engineering design

for additional data using available tools such as Google Earth, maps, and the Web. The quantitative and qualitative data provided for each country include water supply per week, water price, tanker capacity, and ports' facilities. Students can also obtain data about distance between countries, major ports in each country, and tanker oil consumption. After students have developed their model, they are to write a letter to the client detailing how their model selects the best country for supplying water. An extension of this problem gives students the opportunity to review their model and apply it to an expanded set of data. That is, students receive a second letter from the client including data for two more countries and are asked to test their model on the expanded data and improve their model, if needed. This chapter, however, does not report on this extension.

Principles for Designing Model-Eliciting Activities

Engineering model-eliciting problems such as the *Water Shortage Problem* are designed to be thought revealing. The development of such problems is guided by six principles for designing model-eliciting activities (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008). A brief description of the principles and how these have been applied in the design of the *Water Shortage Problem* are presented below.

The Model Construction Principle

A modelling problem should require students to develop an explicit mathematical or scientific construction, description, explanation, or prediction of a meaningful complex system. The models students create should be mathematically and scientifically significant. That is, they should focus on the underlying structural characteristics (key ideas and their relationships), rather than the surface features, of the system being addressed. The *Water Shortage Problem* requires students to develop a model for selecting the best among different countries that can supply Cyprus with water, taking into consideration both the given qualitative and quantitative data and the other necessary data students should obtain.

The Personal Meaningfulness Principle

It is important that students can relate to and make sense of the problematic situation presented in a model-eliciting activity. That is, the problem should be one that reflects a real-life situation and that builds on students' existing knowledge and experiences. Research of the first author (e.g. English, 2008) has shown that by designing model-eliciting activities that are integrated within a classroom's particular learning theme (e.g. caring for the environment), the activities are less likely to be treated as "add-ons" in an already crowded curriculum. These modelling activities thus serve to not only enrich the problem-solving component of the mathematics curriculum but also help students link their learning meaningfully across disciplines including scientific, societal, and environmental studies.

The *Water Shortage Problem* is in line with the Personal Meaningfulness Principle as it is an environmental engineering concern for the majority of students. Water shortage is a significant problem in many nations including Australia, where alternative solutions for water supplies have been debated comprehensively in recent years. Likewise, the lack of drinkable water in Cyprus is a major problem, with homes being supplied with water only three times a week. The water issue features prominently in the Cypriot media and all members of the community, including students, are very concerned. The *Water Shortage Problem* is thus a very meaningful one for students.

The Self-Assessment Principle

According to this principle, students should be provided with sufficient criteria for determining whether their final model is an effective one and adequately meets the client's needs in dealing with the given problematic situation. Such criteria also enable students to progressively assess and revise their models as they work the problem. The *Water Shortage Problem* provides opportunities for students to work in teams to assess the appropriateness of their models for selecting the best country to supply water to Cyprus.

The Model Documentation Principle

Modelling problems should encourage students to externalize their thinking and reasoning as much as possible and in a variety of ways. The need to create representations such as lists, tables, graphs, diagrams, and drawings should be a feature of the problem. Furthermore, the models students construct need to involve more than a brief answer: descriptions and explanations of the steps students took in constructing their models should be included. In the present problem, students are required to document their model by writing a letter to their client, namely, the Ministry of Transportation.

The Model Generalization Principle

The models that students generate should be applicable to other related problem situations; in this case, the models should be applicable to structurally similar engineering problems. The present problem asks students to write a letter explaining the method they used to make their decision "so that the Board can use your method for selecting the best available option not only for now, but also for the future when the Board will have to take similar decisions".

Model-eliciting engineering problems that meet the above principles are designed so that multiple solutions of varying mathematical and scientific sophistication are possible and students with a range of personal experiences and knowledge can tackle them. The products students create are documented, shareable, reusable, and modifiable models that provide teachers with a window into their students' conceptual strengths and weaknesses.

Another important feature of these problems is the opportunities provided for multiple feedback points to encourage students to rethink their models (e.g. through "what-if" questioning) and for discussion on the strengths and weaknesses of their models (with respect to the client's criteria for success) across a classroom full of alternative models. Furthermore, these modelling problems build communication (oral and written) and teamwork skills, both of which are essential to success across disciplines.

The Present Study

Participants and Procedures

Two classes of 38 11-year-old students and their teachers worked on the *Water Shortage Problem* as part of a longitudinal 3-year study that aims to explore students' modelling development as well as enhance students' awareness of basic engineering concepts and processes (e.g. applying engineering design processes, applying science and mathematics learning in engineering, and employing creative

Table 8.1 The water shortage problem data

Country	Water supply per week (metric tons)	Water price, € (metric ton)	Tanker capacity (metric tons)	Tanker oil cost per 100 km (€)	Port facilities for tankers
Egypt	3,000,000	4.00	30,000	20,000	Average
Greece	4,000,000	2.00	50,000	25,000	Very good
Lebanon	2,000,000	5.20	30,000	20,000	Average
Syria	3,000,000	5.00	30,000	20,000	Good

and careful thinking in solving problems). The students were from a public K-6 elementary school in the urban area of a major city in Cyprus.

Engineering and mathematical modelling problems of the present type were new to the students, since current curricula do not include any modelling activities. However, the students were familiar with working in groups and communicating their mathematical ideas to their peers.

As indicated in the Appendix, the *Water Shortage Problem* entails (a) a warm-up task comprising a newspaper article, designed to familiarize the students with the context of the modelling activity; the article focuses on the water shortage problem that a number of countries face nowadays; the article further presents a discussion on the actions these countries could take for solving the problem, (b) "readiness" questions to be answered about the article, and (c) the problem to be solved, including the data (see Table 8.1). Students are asked to use the information provided and any other resources they might find useful to develop a model for ranking the four countries, in order to help local authorities make the best possible choice. After completing the activity, students are to write a letter to the local authorities, documenting the method they used to develop their model.

The problem was implemented by the second author, a postgraduate student, and the classroom teachers. Working in mixed-ability groups of three to four, students spent four 40-min sessions on the activity. During the first session the students worked on the newspaper article and the readiness questions. In the next three sessions, students developed their models and wrote letters to local authorities, explaining and documenting their models. To facilitate student explorations during the development of their models, Google Earth and spreadsheet software were available to them.

Data Sources and Analyses

The data sources were collected through audio- and videotapes of the students' responses to the modelling activity, together with the Google Earth and spreadsheet files, student worksheets, and researchers' field notes. Data were analysed using interpretative techniques (Miles & Huberman, 1994) to identify developments in the model creations with respect to the ways in which the students (a) interpreted and understood the problem, (b) selected and categorized the data sets, used digital maps, and applied mathematical operations in transforming and merging data, and (c) integrated the environmental aspects of the engineering problem. Eight out of the eleven groups of students who worked on the modelling activity succeeded in developing appropriate models for solving the problem. These solutions are summarized in the four different models presented next.

Results

Model A

Four groups developed quite similar models for solving the *Water Shortage Problem*. Students in these groups commenced the activity by agreeing on calculating the distance between Cyprus and other countries. These groups used Google Earth's capabilities for "visiting" the four countries and finding their major ports. Effectively using the software's capabilities (drawing lines and pathways and measuring), students calculated the distance between Cyprus and the other four countries and added new data into a new column of the provided table (see Table 8.2). This process was quite straightforward for the students, since it only involved the software tools' manipulation.

Students then calculated the water cost for each country and ranked the four countries. All four groups selected Greece to supply Cyprus with water, since water from Greece would cost less than water from the other three countries. One group's model development is presented in detail in the following paragraphs.

Students in this group started their explorations by using the "Fly to" command to visit Lebanon. Their initial discussions focused on Lebanon's landscape; they observed that there were many mountains and therefore Lebanon could supply Cyprus with water. Students then explored Lebanon's coast and decided that Tripoli was a major port. They finally added a place mark on Tripoli. Using the "zoom out" command, students then moved to Cyprus and added a second place mark on Limassol, Cyprus' major port. The group used the software's "Ruler" feature to calculate the distance between Tripoli and Limassol. Students repeated their approach and placed place marks on Pireus (Greece), Latakia (Syria), and Cairo (Egypt). Students finally added the new data into the table.

Of interest was students' decision to exclude some of the provided data. Students specifically excluded water supply per week and port facilities factors and did not

Table 8.2 Model A's new data

Country	Water price, € (metric ton)	Tanker capacity (metric tons)	Tanker oil cost per 100 km (€)	Distance
Egypt	4.00	30,000	20,000	420
Greece	2.00	50,000	25,000	940
Lebanon	5.20	30,000	20,000	260
Syria	5.00	30,000	20,000	280

Table 8.3 Final model A

Country	Distance (km)	Oil cost (€)	Water cost per tanker (€)	Total cost (€)	Average water cost per ton (€)
Egypt	420	84, 000	120,000	204,000	6.80
Greece	940	235, 000	100,000	335,000	6.70
Lebanon	260	52, 000	156,000	208,000	6.94
Syria	280	56, 000	150,000	206,000	6.87

include these factors in developing their final model. Using the data presented in Table 8.2, students calculated total *Oil Cost per Trip* by multiplying oil cost per 100 km by distance and then dividing by 100. Students then calculated *Water Cost per Tanker*, by multiplying Water Price by Tanker Capacity, and then calculated *Total Cost per Trip* by adding oil cost and water cost. Students finally calculated the *Water Price per Ton* by dividing the total cost by Tanker Capacity (see Table 8.3). This group (similar to other three groups) decided that buying water from Greece was the best possible solution.

In sum, for model A, mathematical developments were significant in all four groups' work; however, students did not attempt to integrate within their models qualitative data (port facilities) or water supply per week data. Three out of the four groups did not adopt and use these data, since they decided that these data were not related in any way with the problem they had to solve (from which country Cyprus should buy water from). In one group, students identified that water supply per week is an important aspect of the problem, since it might be the case that a country may not be able to supply Cyprus with water, in order to cover all the island's needs. The students, however, decided not to incorporate this factor in their final model. In their words: "We do not know (they referred to the provided table) how much water we need, so how can we decide whether a country can provide Cyprus with water or not . . . let's do not use these data". Also of interest was the absence of any discussion among students about the environmental aspects of the problem.

Model B

Two groups followed the same approach of model A, using the factors presented in that model. Students in these groups also found the major ports in each country and drew tanker routes (see Fig. 8.2).

What was different in these groups' work was their correct and more precise decision to base their calculations on round instead of single route trips. This approach was more advanced than the one presented in model A, since tankers (according to the newspaper article) would start their trips from Cyprus and then work on a round-trip base.

This approach resulted in a more sophisticated and different model, compared to model A. This happened because students calculated twice the Oil Cost (compared to model A). According to their final model, presented in Table 8.4, these two groups

Fig. 8.2 Drawing tanker routes between Cyprus and the other countries

Table 8.4 Final model B

Country	Distance (km)	Oil cost (€)	Water cost per tanker (€)	Total cost (€)	Average water cost per ton (€)
Egypt	420	168,000	120,000	288,000	9.60
Greece	940	470,000	100,000	570,000	11.40
Lebanon	260	104,000	156,000	260,000	8.66
Syria	280	150,000	150,000	262,000	8.73

proposed to local authorities to buy water from Lebanon, since this was the cheapest option.

Although these groups' work differed from that of the previous groups (model A) in that they developed a more refined model (round trip), they nevertheless failed to incorporate in their model factors such as port facilities for tankers and each country's resources for supplying water. These students, similar to previous groups, failed to integrate within their models any of the environmental aspects of the situation.

Model C

This model incorporated components of model A. One group of students followed the same approach and developed an initial model, like the one presented in Table 8.3. However, this group further discussed the various aspects of the problem and questioned the appropriateness of their model, which ranked Greece first.

Students in this group extensively discussed sea pollution. Based on the newspaper article that they worked on during the first session of the modelling activity, one student in the group raised the question of whether it would be wise to buy water from Greece. He mentioned that the distance from Pireus to Limassol was more than three times greater than the distance from Lebanon and Syria, and he proposed to buy water from Egypt or Syria, the second and third country in distance ranking. An extract from the students' discussion appears below:

Student A: It is much better to buy water from a country close to It is much better to buy water from a country close to Cyprus.
Student B: Why?
Student A: It is good to minimize oil consumption. That's why.
Student C: Yes, you are right, but we decided to use water cost per ton in our solution, not only oil consumption.
Student A: I agree. I am not saying to focus only on oil cost. But I believe that we need a solution that takes into account that it is better to buy water from a country near Cyprus, like Lebanon, as to avoid more oil consumption.
Student B: Exactly, especially since oil is getting more and more expensive.
Student A: It is not the only reason. We need to think of the environment. Especially in our case, we need to minimize Mediterranean's pollution from oil and other waste.

Students also documented in their reports that all countries in the Mediterranean Sea should be fully aware of sea pollution and therefore try to minimize ship oil consumption. Another student suggested buying water from Syria, since water price is not that expensive (compared to the price from Greece and Egypt). Students finally ranked countries in the following order: Syria, Egypt, Lebanon, and Greece and decided to propose to the local authorities to buy water from Syria.

Model D

The most sophisticated model created in this activity was developed by another group of students. Compared to the models described previously, more factors were integrated within this model. Specifically, students in this group tried to quantify the port facilities factor and took into consideration the water supply per week data. While students in this group reached a first model similar to the one presented in Table 8.3, they decided to integrate within their calculations the port facilities. A discussion followed, focused on the amount of money necessary for improving the ports' facilities and how this amount of money would change the water price per ton. Students asked their teacher and the researcher for more information about the amount of money necessary for improving port facilities in Syria, Lebanon, and Egypt. Students were surprised when their teacher replied that improving the ports' facilities would cost from five to ten million euro. The following discussion occurred:

Student A: Ten million euro? That's huge. The government cannot pay so much money.
Student B: It is obvious that we will buy water from Greece. It is more expensive than water from the other countries, but at least we will not pay for improving port facilities.
Researcher: I agree with you that ten million euro is not a small amount of money. But, don't you have to think of that amount in terms of the whole project of importing water in Cyprus?
Student B: Do you mean thinking of this amount in comparison to how much importing water in Cyprus will cost?
Researcher: Exactly!

Although students explicitly understood the importance of that factor and how it was related to the water cost, they did not integrate the new data within their model. Further, students at that stage failed to consider in their model development tanker round trips and consequently selected Greece as the best possible country to buy water from.

During their second round of improving their model, students discussed issues related to tanker capacity and oil cost and how these factors might relate to their solution, not only in terms of the mathematical relations. Students were aware of energy consumption issues and they discussed in their group that oil consumption should be kept as minimum as possible. When their teacher prompted them to decide which factor was more important, water price or oil consumption, students replied that it would be better to spend a little more money and to reduce oil consumption. They also made explicit that it was not only oil consumption but also other environmental issues, like the pollution of the Mediterranean Sea, that needed to be considered. Finally, this group resulted in proposing Syria as the best place to buy water from, since it had quite cheap water and it is the closest to Cyprus.

Remaining Groups' Model Creations

Students in the remaining groups faced a number of difficulties in ranking the different countries. In the first component of the problem, using Google Earth for finding appropriate ports and calculating the distances between Cyprus and the three countries, two groups focused their efforts only on Greece, by finding the distance between Pireus and Limassol. Some other groups faced a number of difficulties in using the software itself and/or making wrong calculations in the spreadsheet.

In the second component of the problem, transferring the distance measurements in the spreadsheet software and calculating the different costs, the students faced more difficulties. The majority of their approaches were not successful. Many students, for example, just made random calculations, using partially the provided data, and finally making a number of data misinterpretations. One group, for example, reported that buying water from Greece is the best solution, since the water price per ton from Greece was only €2.00 (see Table 8.1).

Discussion and Concluding Points

Engineering education in the elementary and middle school is important for a number of reasons. Appropriate engineering experiences incorporated within mathematics, science, and technology curricula can (a) help students appreciate how their learning in these subjects can apply to the solution of important real-world-based engineering problems, (b) lead to better preparedness for senior subjects, (c) highlight the relevance of studying mathematics and physical sciences, (d) show students how their technology education provides important foundations for the study of university engineering, (e) help students appreciate the usefulness of the various fields of engineering and the role of the engineer in the society, and (f) enhance students' interest in pursuing engineering as a career (Katehi et al., 2009; Wicklein, 2006; Zawojewski et al., 2008). Students learn how to apply the engineering design process in solving real-world problems; they learn to think creatively, critically, flexibly, and visually; and they learn to troubleshoot and gain from failure.

Model-eliciting activities provide a rich vehicle for introducing engineering education in the elementary and middle school, largely because they focus on "*elicitation* and subsequent successive *alteration* and *generalization* of conceptual models" (Hamilton et al., 2008). Furthermore, as Hamilton et al. note, modelling crosses disciplinary boundaries and develops important concepts and processes that are essential for students' future achievements. For example, the ability to "identify, organize and represent structure", the reasoning skills needed to develop new knowledge structures, and the capacity to document and communicate one's learning are essential foundations for now and the future (p. 9.).

There are a number of aspects of this study that have particular significance for the inclusion of Engineering Model-Eliciting Activities in the younger grades. Although a number of students in the present study experienced difficulties in solving the problem, elementary and middle school students can successfully participate and satisfactorily solve complex environmental modelling problems when presented as meaningful, real-world case studies. The students' models varied in the number of problem factors they took into consideration, how they dealt with these factors, and whether and how they considered important environmental issues. For example, many groups succeeded in identifying dependent and independent variables and in representing elements mathematically, so formulae could be applied. Further, a number of groups of students integrated within their models environmental aspects of the real problem (e.g. energy consumption, sea pollution) and therefore improved their models.

The findings of the present study are also of interest for a number of reasons related to the design and implementation of Engineering Model-Eliciting Activities for young students. First, students need to be encouraged to integrate all available information and even look for more resources and information, especially when they have no prior experience in working with modelling activities. Second, students need to be aware that it is useful and necessary to be able to simplify engineering problems in order to arrive at some initial solutions, which may be refined further at a later stage as needed, using more data. Further, in contrast to traditional problem-solving activities, in modelling activities students often need to quantify information, combine qualitative and quantitative information, and apply decision-making approaches (Mousoulides, Sriraman, & Lesh, 2008). Decision making is not a straightforward process—students need to appreciate through such modelling activities that in engineering problems it is necessary to combine many factors some of which may be conflicting, that there may be multiple objectives that need to be satisfied, and that there is not always a unique solution.

In conclusion, engineering education for younger students is a new and much-needed field of research. The elementary and middle school curricula provide ideal opportunities for introducing students to foundational engineering ideas and principles. We consider it imperative that young scholars develop a strong curiosity and drive to learn how engineering shapes their world and supports so many of our society's needs.

Acknowledgement The Water Shortage Problem has been developed under the ModelMath project, which is funded by the Cyprus Research Foundation. The views expressed are those of the authors and do not necessarily reflect the views of the Cyprus Research Foundation.

Appendix: There Is a Trouble in Paradise: Severe Water Shortage Problem in Cyprus

Nicosia. Alex Chris, a landscape gardener working for several foreign embassies and private estates in Nicosia, said many of the capital's boreholes are now pumping mud. "I installed one expensive garden with 500 meters of irrigation pipe in Nicosia a few months ago," he said. "Last week they called to tell me the system had stopped and their trees and lawns were dying. I found that sludge had been pumped through the pipes and then solidified in the heat. It was like cement".

Last week, people all over Cyprus received a water conservation advisory via mail, reporting "extremely dry conditions in Cyprus as a result of a lack of rain."

The mail suggested several measures the Cyprus Water Board would take to conserve water. Water shortage in Cyprus is among country's most important problems. However, water shortage is common in much of the world. In fact, half the planet's population is expected to face an insufficient water supply by 2025.

Emergency water rationing as well as a request to import water from nearby countries was ordered as a result of a severe water shortage due to a drought over the last four years. Reservoir reserves have plunged dangerously low and desalination plants cannot keep up with a growing demand for water. Cyprus has two desalination plants running at full capacity, with a third due to come on stream in June. The island's reservoirs are now 10.3 percent full and there has been little rainfall since 2003. "Cuts are essential to cover the needs of the population. This is an extremely grave situation," said a government spokesman. The island is increasingly relying on desalinization plants for water, but they can only provide 45% of demand, and their operation is energy heavy. The head of the Cyprus Water Board said: "We don't desalinate lightly, without being aware of the consequences. It is energy-consuming . . . and this causes (greenhouse gas) emissions Cyprus that has to pay fines for."

Water has always been a valuable commodity on the Mediterranean island, which has one of the world's highest concentrations of reservoirs. The country is used to regular periods of drought due to its location and climate, but there has been a sharp decrease in rain in the past 35 years. Since 1972, rainfall has decreased 20% and runoff into reservoirs has decreased by 40%. The demand for water in Cyprus, for now, outstrips supply. Experts estimate the island will need almost 5,09 million cubic meters of water until the new year. Kouris, one of the island's largest and most important dams, currently stands less than 2.5% full, with 3.23 million tons of water.

Cypriot officials decided to sign a contract with a nearby country to import more than 12 million cubic metres over the summer period starting at the end of June. Officials will also sign a contract with a shipping company to use oil tankers for supplying Cyprus with water. The tanker supply program will continue until a permanent solution to the problem has been reached. The water will be pumped directly into the main water supply pipelines with any surplus going to the reservoirs.

Readiness Questions

1. Who is Alex Chris?

2. What is Kouris?

3. How many desalination plants for water are currently in Cyprus?

4. Why does the Cyprus government not build more desalination plants to cover the country's water needs?

5. Which solution did the Cyprus Water Board decide to adopt for solving the water shortage problem?

The Problem

Cyprus Water Board needs to decide from which country Cyprus will import water for the next summer period. Using the information provided, assist the Board in making the best possible choice.

Lebanon, Greece, Syria, and Egypt expressed their willingness to supply Cyprus with water. The Water Board has received information about the water price, how much water they can supply Cyprus with during summer, oil tanker cost, and the port facilities. This information is presented below.

Write a letter explaining the method you used to make your decision so that the Board can use your method for selecting the best available option not only for now, but also for the future when the Board will have to take similar decisions.

Letter

Dear Water Management Board,

Our team, ____,
decided that Cyprus should buy water from ____________. Our work resulted in the following ranking:
____.

The method we followed for ranking the different countries is:
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Best regards,
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Chapter 9
Engaging Elementary Students in Scientific Modeling: The MoDeLS Fifth-Grade Approach and Findings

Hamin Baek, Christina Schwarz, Jing Chen, Hayat Hokayem, and Li Zhan

In the recent past, educators have increasingly advocated engaging learners in authentic disciplinary practices (Brown, Collins, & Duguid, 1989; Schoenfeld, 1999). Aware of the limitations of learning decontextualized knowledge and skills, they have emphasized students' participation in scholarly communities' ordinary activities including their discourse, social interactions, and use of material and intellectual tools. As part of this effort, research-based reforms in science education have emphasized the importance of engaging learners in scientific practices that represent disciplinary norms. The goal of this engagement is to help learners understand how scientific knowledge is constructed, evaluated, and communicated and to use scientific knowledge and practices in their own lives (Duschl, Schweingruber, & Shouse, 2007). In particular, science educators have attempted to foster scientific practices such as scientific explanation (McNeill, Lizotte, Krajcik, & Marx, 2006), argumentation (Berland & Reiser, 2009), and modeling (Lehrer & Schauble, 2006). Outcomes from this work indicate that involving learners in these practices can help them develop more sophisticated understandings of the nature of scientific knowledge and inquiry.

Engaging in scientific practices, however, entails more than acquiring new skills: It requires one to adopt the scientific community's "Discourse," a term Gee (2005) coined to indicate "ways of combining and integrating language, actions, interactions, ways of thinking, believing, valuing, and using various symbols, tools, and objects to enact a particular sort of socially recognizable identity" (p. 21). Effectively engaging students in scientific practices is challenging given the large discrepancies between the traditional classroom norms and the norms of the scientific community (Berland & Reiser, 2009; Jiménez-Aleixandre, Rodríguez, & Duschl, 2000). As a result, both teachers and students need support through professional development and strong curriculum materials (Duschl et al., 2007).

The *Modeling Designs for Learning Science* (MoDeLS) project has been engaged in research to make the practice of scientific modeling meaningful and accessible for students in the upper elementary and middle school grades. To that

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_9,

end, the project has been working with schools and teachers to develop a learning progression of scientific modeling. A learning progression is a description of how learners become successively more sophisticated in reasoning and practices on a given topic as they learn about the topic over a broad (e.g., several years) time period (Duschl et al., 2007). As part of developing our learning progression, the project has supported students and teachers by providing curriculum materials, teacher education, and professional development.

In this chapter, the authors present our approach toward engaging fifth-grade elementary students in scientific modeling within the MoDeLS project. After describing our conceptual and methodological frameworks, we discuss the model-centered instructional sequence (MIS) that we developed and incorporated into our fifth-grade modeling-centered curriculum unit on evaporation and condensation and how the unit was implemented. Finally, we report on the empirical outcomes of our approach in two fifth-grade classrooms, examining the effects of MIS components on students' modeling practices.

The MoDeLS Approach to Scientific Models and Modeling

Conceptual Framework

In alignment with current research of learning about modeling (Lehrer & Schauble, 2006; Lesh & Doerr, 2003), we define a scientific model as "a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena" (Schwarz, Reiser, Davis et al., 2009, p. 633). Examples of scientific models include the wave model of light, the Bohr model of the atom, and the food web model describing interactions between organisms. Scientific models are distinguished from other representations in that they embody mechanism, causality, or other features to illustrate, explain, and predict phenomena. Models can be further classified into mental models and expressed models (Gobert & Buckley, 2000). Mental models refer to the individual's internal representations of the explanatory mechanism, predictive patterns, and laws that underlie natural phenomena. Expressed models are external representations of the target phenomenon constructed from one's mental models. They include diverse forms such as speech, written descriptions, drawings, and computer simulations. Expressed models enable one to communicate, test, and develop one's internal models. When discussing models in this chapter, we primarily refer to the expressed models in students' drawings.

Scientific models are crucial artifacts that scientists utilize in their inquiry of natural phenomena. Nonetheless, introducing them to K-12 classrooms without considering their use may not be of much help to students. Scientists' modeling practices are complex and may hinder rather than promote students' access and meaning when transferred to school settings. To address this difficulty, we drew upon previous research on student learning about modeling (Clement, 2008; Spitulnik, Krajcik, & Soloway, 1999; Stewart, Cartier, & Passmore, 2005; White &

Frederiksen, 1998) to identify four elements of modeling practice that are central as well as accessible for learners (see Schwarz, Reiser, Davis et al., 2009):

- *Model construction*: Students construct models consistent with prior evidence and theories.
- *Model evaluation*: Students compare and evaluate different models using criteria such as explanatory power and consistency with empirical evidence.
- *Model revision*: Students revise models to increase their explanatory and predictive power, taking into account additional evidence or explanatory features.
- *Model use*: Students use models to illustrate, explain, and predict phenomena.

We argue that these components of modeling practice represent core aspects of modeling as practiced by scientists and are pedagogically accessible for learners. Furthermore, as students engage in these practices[1] they are likely to develop more sophisticated understanding of how scientific knowledge is generated and evolves.

Besides our emphasis on the modeling practices, we are also committed to enabling learners to obtain metacognitive knowledge about modeling practice that makes the practice meaningful. For example, learners need to understand the nature and purpose of models and modeling in order to more productively engage in modeling as well as appreciate how science works and the dynamic nature of knowledge that science produces (Abd-El-Khalick et al., 2004). This knowledge about modeling is a type of understanding of the nature of science (Lederman, 2007) that we refer to as *metamodeling knowledge* (MMK) (Schwarz & White, 2005). Modeling practices and underlying knowledge are more powerful and meaningful when addressed in combination rather than treated as separate components. MMK guides the practices by making the purpose and nature of the practice explicit and accessible. At the same time, students' first-hand experiences with modeling practices make MMK sensible and useful.

Methodological Framework: A Learning Progression Framework for Students' Scientific Modeling

The MoDeLS project has been engaging students in scientific modeling at the upper elementary and middle school grade levels across several science domains. Those domains include physical science (light, matter) as well as biological sciences (ecosystems). In doing so, our work has focused on the practice of scientific modeling itself, rather than on the scientific content within specific models. (Schwarz, Reiser, Fortus et al. 2009). While we value the importance of learning about specific scientific models, our primary goal is to gain an insight into the process of abstracting and generalizing knowledge about specific models. Examining general aspects

[1] Hereafter, we use "modeling practices" to refer to the components of modeling mentioned above.

of modeling practice is important if we want to apply such an approach across a wide range of models and scientific phenomena.

In order to capture general features of modeling across different grades and contexts, the MoDeLS project has been working on the development of a learning progression framework. Conducting our work as a design experiment (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003), the project team has been involved in an iterative process of constructing, testing, and revising a learning progression for scientific modeling. The initial framework was constructed on the basis of preexisting research and theoretical conjectures. Instructional interventions have generated empirical data of students' modeling to refine and validate the learning progression. The empirical data from these interventions have then been used to inform and revise the learning progression framework (see Schwarz, Reiser, Davis et al., 2009, for further information on the initial framework and outcomes).

As a result of this iterative process, we produced a construct map with two dimensions of modeling practice (see Schwarz, Reiser, Davis et al., 2009). In one dimension ("generative"), the map focuses on how students construct and use models to generate scientific knowledge. Another dimension ("change") concerns how and why students revise and evaluate their models. For both dimensions, we have refined the construct map to include four sub-dimensions that capture more detailed and empirically accurate aspects of students' progression within those practices. We used these dimensions to code our data, giving rise to some of the patterns reported in this chapter. The four sub-dimensions focus on

A. the extent to which students note *salient and general features of models* and represent this in their modeling practices,
B. the extent to which students consider *communication* in their models and whether the purpose of that communication is for themselves, others, or the content being communicated,
C. the extent and nature of how students consider the *source of knowledge or evidence* in their models as well as the reflection of that consideration in their modeling practices,
D. the explanatory aspects of phenomena in students' models (general explanation, process, mechanism) as well as students' reflections about the explanatory aspects of the phenomena.

For each sub-dimension, we developed level descriptions in alignment with empirical data that chart the potential progression a student might make from less to more sophisticated modeling practices. For instance, level descriptions for "generative sub-dimension A" are as follows:

- Level 1: *Models are used as a literal representation of a real thing, which is accessible to our senses.*
- Level 2: *Models are constructed and used to show things that are inaccessible to our senses (e.g., forces, energy, size, and scale).*
- Level 3: *Models are constructed and used to show or predict aspects of a group of related phenomena. Individual models' components can be combined since each model has advantages and weaknesses.*

- Level 4: *Models are constructed and used prior to observing phenomenon, as representing a "what-if" world.*

As previously stated, the sub-dimensions and levels of this learning progression framework have provided a lens for the analysis of our data—leading to some patterns in outcomes noted in this chapter. For a more comprehensive learning progression framework including both "generative" and "change" dimensions, see other manuscripts (Hokayem, Chen, Baek, Zhan, & Schwarz, 2010; Schwarz, Reiser, Davis et al., 2009; Schwarz, Reiser, Fortus et al., 2009).

The Model-Centered Instructional Sequence and the Unit of Evaporation and Condensation for Elementary Students' Engagement in Scientific Modeling

The Authors' Work on Engaging Elementary Students in Scientific Modeling

The approach and findings reported in this chapter focus on elementary students' engagement in scientific modeling and are situated within the MoDeLS work that has taken place across multiple institutions (Schwarz, Reiser, Davis et al., 2009; Northwestern University, 2009).

The authors have worked with two teachers and about seventy fifth-grade students at two public elementary schools in a midwestern state during the 2008 school year. We developed a 6- to 8-week curriculum unit on scientific modeling of evaporation and condensation. The teachers then implemented the unit in their science classes. Although the curriculum materials specified instructional and learning moves in detail, the authors' sought a significant amount of teacher input for the implementation and modification of materials. Doing so made the approach feasible and fostered the researcher–teacher collaboration as well as the development of teachers' knowledge and professional practice—necessary for facilitating students' engagement in modeling practice.

Before turning to the outcomes of the approach, we describe the role of instructional sequencing and the model-centered instructional sequence (MIS) we developed for the curriculum unit on evaporation and condensation. We outline arguments for why such an approach is potentially useful for fostering elementary students' practices in scientific modeling.

The Instructional Sequence as a Pedagogical Tool

There has been a long history of scholarly interest in instructional sequences. While using diverse terms such as "learning cycle" (Abraham, 1998; Atkin & Karplus, 1962; Heiss, Hoffman, & Obourn, 1950), "instructional model" (Bybee, 1997), "design framework" (Edelson, 2001), "instructional framework" (Schwarz &

Gwekwerere, 2007), “teaching–learning sequence” (Méheut & Psillos, 2004), and “instructional sequence” (Douglass & Kahle, 1978; Guisasola, Almudi, Ceberio, & Zubimendi, 2009), scholars have commonly emphasized the role of sequencing activities for fostering student learning. Building on this research tradition, we conceptualize “instructional sequence” to mean a framework or model that coherently sequences teaching and learning activities to enhance learners’ knowledge, practices, and attitudes within a given topic.

Recent studies about instructional sequences have most commonly aligned with the conceptual change research tradition. Their focus has been on the design, implementation, and evaluation of an instructional sequence that typically spans several weeks and centers on a single topic such as optics, electromagnetism, and the structure of matter (Méheut & Psillos, 2004). Such work has emphasized the effects of instructional sequences on students’ reasoning and knowledge about scientific topics. In addition to the benefits of the cognitive approach, we also find sociocultural approach useful for the MoDeLS work because it offers a comprehensive lens to allow one to see a practice as a socioculturally and historically formed “activity system” that entails multiple components of a Discourse of a community that embraces the practice (Engeström, 1987; Gee, 2005; Lave & Wenger, 1991; Rogoff, 2003; Roth & Lee, 2007). A sociocultural approach addresses not only ways of obtaining scientific knowledge with models but also ways of using tools (e.g., models, laboratory devices, computer software, symbols), ways of performing social interactions around modeling (e.g., communication, division of labors), and social values and norms embedded in this collective activity. From this perspective, the instructional sequence is a pedagogical tool not just for helping students change their conception of a practice but for fostering their extensive participation in a “community of practice” (Lave & Wenger, 1991; Wenger, 1998).

The Model-Centered Instructional Sequence (MIS)

In an attempt to facilitate students’ engagement in scientific modeling, we developed an instructional sequence that incorporates modeling practice as a core element, which we call the *model-centered instructional sequence* (MIS). Based on previous studies on curriculum design (White & Schwarz, 1999), middle school students’ modeling (Schwarz & White, 2005), and preservice modeling-centered inquiry (Schwarz & Gwekwerere, 2007), MIS was crafted as a general instructional framework for incorporating modeling practice in multiple content areas (Kenyon, Schwarz, & Hug, 2008). Though we do not suggest that this approach works seamlessly for every content area, we hypothesize that using MIS in multiple elementary contexts will help both students and teachers to effectively engage in this potentially new and complex practice.

MIS has several features that are likely to be important in bringing scientific modeling practice into school science (see the MIS description in Table 9.1). Each of these features is intended to help students acquire a specific aspect of the scientific Discourse involved in scientific modeling.

Table 9.1 The Model-centered instructional sequence (MIS)

Components	Modeling practices	Description
Anchoring phenomena and central questions		Phenomena easily found in students' everyday life or potentially intriguing to them are introduced Key questions on the anchoring phenemena ensue. These questions for which they do now know an answer (and must investigate using knowledge and practices in the upcoming unit) give students opportunity to come up with ideas or hypotheses that may help answer the questions
Constructing an initial model	Model construction	Individual students construct an initial model that encompasses their idea or hypothesis for answering the central questions in ways to help them outline how they might gather evidence and test their ideas. This model can take different forms such as drawing, 3D artifact, and computer simulation
Empirical investigations		Students in groups conduct a set of empirical investigations about the phenomena. The experiments are strategically chosen to provide evidence that might be useful for addressing the central question and for revising the models. For each experiment, students *predict* the outcome (based on their initial model), *share* their prediction with others, *observe* as they conduct the experiment, *analyze* the patterns they find, *explain* the result, and *reflect* the result in relation to their model
Scientific ideas and computer simulations		Fundamental scientific ideas and theories related to the general phenomena or model (and not accessible through empirical investigations) are introduced—through text, the teacher, or other validated sources such as computer simulations. Students interact with computer simulations that enact and define ideas about the nature and theory of the phenomena. Students discuss the relevant scientific ideas and the simulation models
Evaluating and revising the model	Model revision Model evaluation	Students evaluate and revise their model on the basis of the empirical evidence and the ideas from simulations
Peer evaluation	Model evaluation	In small groups, each student presents his/her model and the others give their evaluative feedback on it. Throughout the process, they discuss criteria for evaluating models
Constructing a consensus model	Model construction	Students compare various models and construct a consensus model either within a small group or as a whole class. This consensus model depicts a general model for the phenomena that best predicts and explains the phenomena by drawing from the strengths of each individual's models
Using the model to predict or explain related phenomena	Model use	Students use the consensus model to predict or explain other related phenomena. They determine strengths and limitations of their model for further revision

First, the MIS sequence includes "model evolution" (Clement, 2008; White & Frederiksen, 1998) as a central feature. Contrasting with a simpler approach that begins with the teacher's presentation of a sophisticated set of scientific models at the outset, MIS takes an alternative approach in which students begin by constructing their own models and continue to evaluate and revise those incomplete models as they gather further information such as empirical evidence and advanced explanatory features. We theorize that this sequencing helps cultivate authentic scientific inquiry about and with scientific models among students. This becomes apparent when model-based scientific inquiry in MIS is contrasted with the widely (mis-) practiced school science inquiry known as "the scientific method" (Windschitl, Thompson, & Braaten, 2008). In the traditional school-based scientific method, students often construct a hypothesis much like a prediction, confuse patterns in empirical data with a conclusion to the hypothesis, and do not link the conclusion (patterns) to an explanatory theory or model. In contrast, model-based inquiry engages students in scientists' authentic inquiry they perform with models which bears the feature of model evolution.

Second, we included empirical investigations in MIS with an intention to provide students an opportunity to recognize and utilize the significant role of empirical evidence in modeling. Departing from a naïve understanding that scientific knowledge can be obtained directly from natural phenomena, we support the idea that scientific knowledge is constructed through processes that involve various—material and symbolic—tools and are considered legitimate in the scientific community (Latour & Woolgar, 1979). Of such processes, empirical investigation has been highly valued in the scientific community's epistemic enterprise. By incorporating this feature in MIS, we hoped that students would be able to appreciate a foundational role of empirical evidence as they tried to resolve discrepancies they might find between their prediction based on their model and the empirical evidence they would have. Further, we hoped to find them utilize empirical evidence in their modeling practice—primarily in model evaluation and revision (since these practices come after empirical investigations in MIS) and also in model construction and use.

Third, computer simulations in the MIS are intended to introduce students to scientific explanation of natural phenomena. While the nature of scientific explanation is an ongoing subject in philosophy of science (Woodward, 2010), we think it is important to have students note and appropriate some scientific explanatory features from simulations in their modeling practice. Because ways of explaining in students' everyday lives are somewhat different from scientific explanation (for example, students tend to tell stories or narratives in their everyday discourse), we expected students to benefit from being exposed to scientific ways of explaining phenomena in computer simulations. As they see the explanatory features of computer simulations such as animated mechanisms, students might appropriate some of these mechanisms in their own modeling practice.

Finally, we aimed to introduce scientists' social interactions and norms by including peer evaluation and consensus model construction in MIS. Ways in which students interact with one another and the social norms that govern those interactions are disparate from scientists' interactions and social norms. Some researchers have attempted to understand and bridge this gap (Berland & Reiser, 2009; Herrenkohl & Guerra, 1998; Jiménez-Aleixandre et al., 2000; Roth & Bowen, 1995). Drawing upon this research, we designed MIS such that students engage in different intellectual roles (e.g., model presenter and model evaluator in peer evaluation; collaborators in the construction of consensus models) and base their collective model evaluation on criteria beyond personal preference (e.g., consistency with empirical evidence, explanatory power, and communicative effectiveness). By engaging in these activities, students might begin to understand how scientists interact with other scientists and what they value in their interactions. These experiences might, in turn, advance students' modeling practices and make such practices more meaningful.

The MIS-Embedded Unit of Evaporation and Condensation

After developing MIS, we incorporated it into a unit of evaporation and condensation for fifth-grade students. For a more complete description of the unit, see Kenyon, Schwarz, and Hug (2008). The unit begins with the anchoring phenomenon of a solar still. A solar still is a device that purifies some forms of polluted water through evaporation and condensation. Students are asked two central questions: "Would you drink the liquid in the bottle cap that came from this dirty water? Do you know what that liquid is and how it got there?" Next, the unit is broken into two sequential sections, one on evaporation and the other on condensation within which students conduct in-depth investigations of the two major phenomena.

The evaporation section starts with its own anchoring phenomenon that guides central questions for the investigations. Students see two pictures showing water on a plate disappear over time and are asked, "What happens to the puddle or water on the plate? Where does it go? How? Why?" Students draw their first model of evaporation (model 1) to answer these questions on their workbook. Next, students conduct a set of empirical investigations about evaporation to test their model. For instance, students measure humidity over time in a container in which a cup of water is placed to determine where the water evaporates. To support this activity and other investigations, the authors provided teachers and students with equipment such as humidity detectors and a weight scale. After conducting the empirical investigations, students discuss how the patterns in the empirical evidence they have collected inform their model. They write down their ideas for revising their model on their workbook. Next, a teacher gives a mini-lecture about basic scientific ideas related to the phenomenon and shows students computer simulations about the phenomenon (see Fig. 9.1 as an example). Using the empirical evidence and the ideas from the computer simulations, students evaluate and revise their initial model and construct a second model of evaporation (model 2). Next, students present their model to others in each group for feedback and discuss criteria for models. They then use these criteria as they construct a consensus model, which is their third model of evaporation (model 3). Finally, they use the consensus model to try to explain or predict other phenomena related to evaporation that they can observe in their daily life.

Students then begin exploring condensation, going through the same process as in evaporation. After viewing a picture showing a bottle with condensation on the outside, they construct their first model of condensation (model 4). Using ideas they

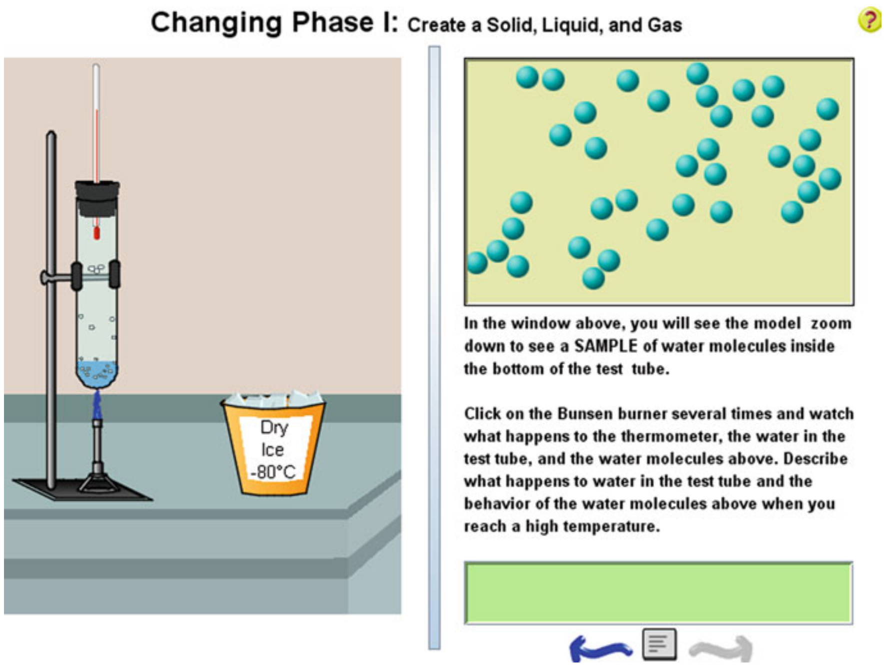


Fig. 9.1 A computer simulation showing phase change (The Concord Consortium, 2010)

collect as they conduct empirical investigations and see related computer simulations, they make a second model of condensation (model 5). This is followed by peer evaluation and construction of a third consensus model of condensation (model 6). Finally they apply their model of condensation for new, albeit related, phenomena.

After completing these two sections, students return to the anchoring phenomenon of solar still and the central questions. Combining information, knowledge, and resources they have acquired through the entire unit, students construct a model of the solar still to answer the central questions. Additional details about the unit are summarized in Table 9.2.

Method

To assess how effective MIS was in improving elementary students' modeling, we collected several sources of data for one teacher's students ($N = 34$).[2] These data sources include (1) the students' responses in written pre- and posttests (for the description and characteristics of the analyzed items, see Table 9.3), (2) their models of evaporation and condensation they drew during the unit implementation, and

[2]We analyzed data from one of the two teachers who implemented the unit during 2008–2009 because his pre–post assessments were identical to one another and to those used by the larger MoDeLS research group.

Table 9.2 The MIS-embedded curriculum unit on evaporation and condensation

MIS components	Content	
Anchoring phenomenon and central questions	Solar still: Would you drink the liquid in the bottle cap that came from this dirty water? Do you know what that liquid is and how it got there?	
	(1) Evaporation	**(2) Condensation**
Anchoring phenomenon and central questions	Water drops disappearing on a puddle/plate: "What happens to the water on the puddle/plate? Where does it go? How? Why?"	Water drops forming on the plastic wrap covering a cup: "What are the drops on the inside of the beaker and on the plastic wrap? Where did they come from? How did they get there?"
Construct a model	Students construct their initial model of evaporation	Students construct their initial model of condensation
Empirical investigations	Compare what happens over time in an open cup and a covered cup What happens to the three cobalt chloride strips placed in different distances from a humidifier? Measure the humidity from evaporating water Measure the humidity from hot and cold water Measure the humidity from wide and narrow beakers	What happens on a cold Coke can over time? What happens on a cold colored Gatorade over time? What happens on a cold mirror over time? Measure the weight of a cold Coke can over time Measure the humidity around a cold Coke can over time Compare what happens to the surfaces of hot and cold Coke cans near a humidifier
Scientific ideas and computer simulations	The teacher gives a mini-lecture of central ideas related to evaporation based on explanations in the student workbook. Students view computer simulations about state change, evaporation, and condensation on the screen	The teacher gives a mini-lecture of central ideas related to condensation based on explanations in the student workbook. Students view computer simulations about state change, evaporation, and condensation on the screen
Evaluate and revise the model	Using ideas collected from the empirical evidence, mini-lecture, and simulations, students evaluate and revise their model of evaporation	Using ideas collected from the empirical evidence, mini-lecture, and simulations, students evaluate and revise their model of condensation
Peer evaluation	Students share their second model of evaporation in a group to obtain feedback from their peers	Students share their second model of condensation in a group to obtain feedback from their peers
Construct a consensus model	Students compare different models of evaporation and collectively construct a consensus model	Students compare different models of condensation and collectively construct a consensus model
Use the model to predict or explain	Students apply their model to explain: perfume, paint drying, dish drying, sanitizing alcohol, sweat, etc.	Students apply their model to explain water on mirror after bath/shower, rain water condensing from clouds, the water on their cold lunchbox container, dew, etc.
Back to the main phenomenon	Students explain the solar still by drawing a model using the consensus models of evaporation and condensation and answer the central questions raised at the beginning of the unit	

Table 9.3 Written assessment items analyzed for assessing students' modeling practices

Modeling practices	Item number	Description	Characteristics
Model construction	1	Make a drawing that shows how the liquid get in the bottle cap within a solar still	Anchoring phenomenon of the unit
	2	Make a drawing or drawings that can explain what happened to the water in an open cup and the water in a covered cup	Phenomenon closely related to evaporation and condensation
	3	Make a drawing or drawings that can explain why a box goes fast on the floor and slow on the rug	Unfamiliar context
Model evaluation	4	Evaluate Cosette's model of evaporation and condensation	Familiar context
	5	Evaluate Makayla's model of evaporation and condensation	Familiar context
	6	Evaluate Grace's model of evaporation and condensation	Familiar context
	7	Evaluate four models of plant growth	Unfamiliar context
Model revision	8	Do scientific models change? Why or why not?	
	9	Do scientists change their models? Why or why not?	
Model use	10	Use your drawing to explain what happens to a marker without the top	Less familiar but related context
	11	Use your drawing to explain what happens to a truck on a dry road and another on a wet road when they try to stop	Unfamiliar context

(3) audio-recorded post-interviews that lasted up to an hour and were conducted with six students selected across a range of achievement levels by their teacher.

In analyzing these data, we paid particular attention to the influence of empirical investigations, computer simulations, and social interactions (peer evaluation, consensus model construction) of MIS, the features that we highlighted earlier as important factors for the improvement of elementary students' modeling.[3] To capture the effects of these features, we took two steps in analyzing the data. We first analyzed the data using the learning progression framework discussed earlier. While this framework was useful to observe general trends in students' reflective practice, it did not directly address the potential influence of the MIS on students' practices. Therefore, we used and refined the learning progressions sub-dimensions to look for

[3]Note that of the four features of MIS—"model evolution," empirical investigations, computer simulations, and social interactions—we discussed earlier, we assess the last three features here. This is because our method does not include comparison of MIS with another instructional sequence that does not contain the feature of model evolution.

outcomes potentially related to the MIS features in the written assessment and interview analysis. We then refined the target of our analysis for each feature, recoded the data, and analyzed workbook data for additional information. For example, to determine the influence of computer simulations, we looked at patterns from pre–post assessments and interview analysis using sub-dimension A (salient and general features of models) and D (general explanation, process, and mechanism represented in models) as those were most likely to indicate the extent to which students extracted the explanatory features of computer simulations for their models. These patterns pointed to the importance of coding for the presence of particles and their movement as students' models throughout the unit. We then recoded students' pre-post assessments, interviews, and workbooks to look more precisely and systematically at this feature. We used a similar strategy for analyzing the influence of empirical investigations—coding for the presence of experiment devices or empirical evidence. To attend to the social aspects of modeling, we coded for the presence of communicative features such as labels.

The Influence of the MIS on Students' Modeling

In what ways did these features of MIS influence elementary students' modeling practices? Analysis of data indicates patterns in students' practices related to empirical evidence, explanatory features, and attention to audience and communication.

The Influence of Empirical Investigations in MIS: Students' Attention to Empirical Evidence

In order to determine the extent to which students attended to empirical evidence and used it in their modeling, we analyzed students' pre–post assessments, models in students' workbooks, and student interviews. The analysis produced mixed results. Analysis of the pre–post written assessment data indicates that almost no students attended to empirical evidence in their modeling practices before or after the unit (see Table 9.4A). The only item for which we found a difference was item 3. This item asked students to construct a model to explain motion with and without friction, which was not a topic students learned about in class. For this item, two students expressed their attention to empirical evidence in the post-assessment whereas none did so in the pretest. One student drew an imaginative "friction meter" and the other a thermometer to show how much friction was present in each condition. It appears that these two students understood and could use this understanding of instrumentation and empirical evidence in their modeling even in an unfamiliar topic area. Nonetheless, the written pre–post assessment provides no other indication that students attended to the role of empirical evidence in modeling.

On the other hand, analysis of students' models in their workbooks throughout their unit indicates that students increasingly included empirical data in their revised models. In Fig. 9.2a, no student included empirical evidence in their initial model of

Table 9.4 Result of the written assessment analysis ($N = 34$)

Modeling practices	Item number	(A) Empirical evidence		(B) Invisible objects		(C) Communicative features	
		Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Model construction	1	0(0.0%)	0(0.0%)	9(26.5%)	18(52.9%)	15(44.1%)	17(50.0%)
	2	0(0.0%)	0(0.0%)	5(14.7%)	20(58.8%)	5(14.7%)	12(35.3%)
	3	0(0.0%)	2(5.9%)	10(29.4%)	15(44.1%)	20(58.8%)	23(67.6%)
Model evaluation	4	0(0.0%)	0(0.0%)	5(14.7%)	11(32.4%)	6(17.6%)	11(32.4%)
	5	0(0.0%)	0(0.0%)	6(17.6%)	11(32.4%)	6(17.6%)	11(32.4%)
	6	0(0.0%)	0(0.0%)	17(50.0%)	21(61.8%)	17(50.0%)	21(61.8%)
	7	0(0.0%)	0(0.0%)	4(11.8%)	10(29.4%)	4(11.8%)	10(29.4%)
Model revision	8	3(8.8%)	1(2.9%)	3(8.8%)	1(2.9%)	2(5.9%)	1(2.9%)
	9	2(5.9%)	0(0.0%)	2(5.9%)	0(0.0%)	2(5.9%)	2(5.9%)
Model use	10	1(2.9%)	0(0.0%)	1(2.9%)	0(0.0%)	0(0.0%)	0(0.0%)
	11	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)

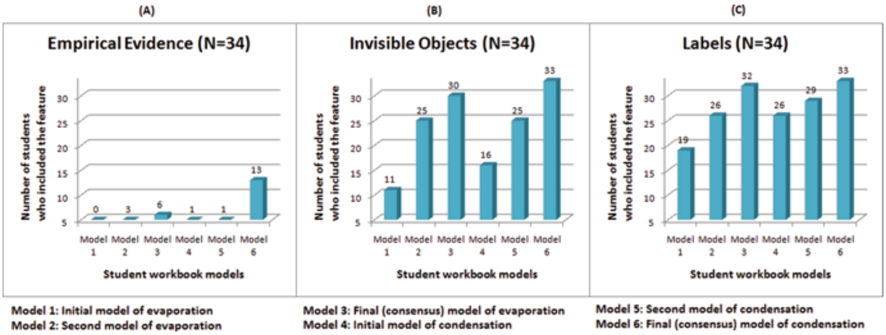


Fig. 9.2 Students' inclusion of empirical evidence, invisible objects, and labels in their models during the unit implementation

evaporation (model 1) compared to six students in their final model of evaporation (model 3). Similarly, the number of students who included this feature in their condensation models increased from 1 (model 4) to 13 (model 6). Although much of these changes may be attributed to the teacher's scaffolding since these final consensus models (model 3 and model 6) were constructed under their teacher's guidance, we can still see some influence of empirical investigations between the initial two models. For instance, no students included evidence in model 1 compared to three in model 2. At the same time, though, the fact that the overall number of students who included this feature in their models is relatively low compared to Fig. 9.2b, c reveals that many students did not find this feature necessary for their models.

Analysis of the interview data indicates that five out of six students recognized and spoke about the role of empirical evidence in model revision. For example, when asked about the difference between his initial and final model, one student stated

Student	For this one (final model), I did warm air and humidity level and in this one, this one (humidity level before condensation) is high and this one (humidity level after condensation) is low. I put the water molecules in the warm air around it. … And for this one (initial model), I didn't put how the air and humidity level is. I did put droplets on it but I didn't put water molecules.
Interviewer	So talk about here—look at the humidity level, here's high and here's low. Why is the humidity level high here and low here?
Student	Because all the water molecules haven't stuck to the thing yet and it's really high humidity. But after it's out, they all come and stick.

This interview shows how the student uses the change of humidity level in the air as an authoritative knowledge source supporting the occurrence of condensation. This information about relative humidity was only made explicit through data from the empirical investigations in the unit. In the following excerpt, another student discusses the importance of evidence for providing information when responding to a question about scientists' model revision:

Interviewer	So do you think that scientists also change their models?
Student	Yes
Interviewer	Why?
Student	Their ideas change and how they think of things. Because if you first have an idea of something and then you do some research on it and find out more information, then their ideas kind of change because they know a little more. So they can get a better idea of what actually happens or what actually causes it to happen.
Interviewer	Okay. Could you talk more about the research? What do you mean by research?
Student	Well, if you go into it more and do some experiments, try and find out information.

This student clearly notes that information from experiments is an important factor that affects scientists' model revision.

Taken together, the patterns in these data indicate several aspects. We found that some students did acquire a more sophisticated understanding of the epistemic role of empirical evidence in advancing scientific knowledge through model revision, particularly when explicitly asked in their interviews. However, this awareness was not frequently reflected in their models. The lack of explicit inclusion of empirical evidence in models may be a result of students thinking they did not need to include empirical evidence in their models because it was implicit in their models. The result of the written test analysis may indicate that students did not manifest this understanding in their modeling practices when the contexts did not explicitly involve discussing empirical evidence. The overall analysis of three different data sources indicates a modest effect of empirical investigations in MIS on students' modeling. Although students' understanding of the epistemic role of empirical evidence in models was limited, we see potential in the fact that some students increasingly appreciated the role of empirical evidence and even tried to retain this feature in their modeling for an unfamiliar context (item 3).

The Influence of the Computer Simulations in MIS: Students' Attention to Invisible Objects as an Explanatory Feature

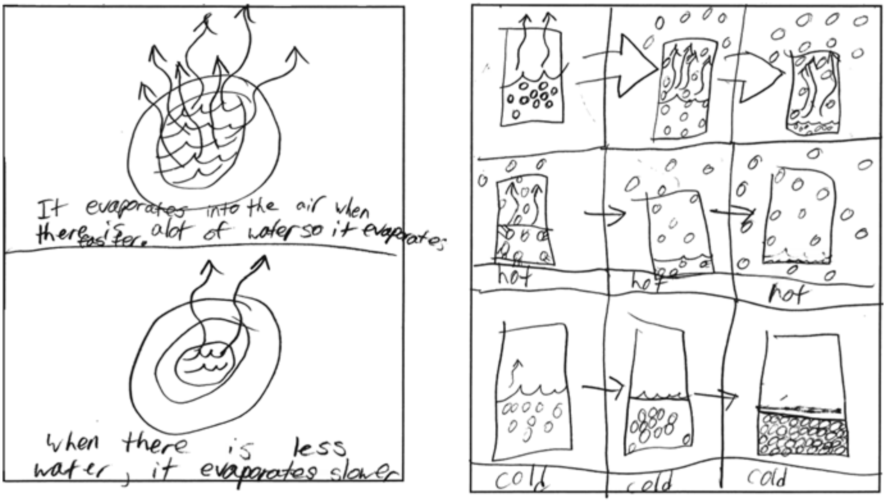
To capture which explanatory features students adopted within the MIS, we again analyzed pre–post assessments, students' workbook models, and post-interviews. Our analysis indicates that many students increasingly included invisible objects and frequently included their movement as an explanatory feature in their models. Our analysis of the written assessments suggests that more students attended to and made use of invisible objects in the posttest than in the pretest with respect to constructing and evaluating models. In Table 9.4B, for example, analysis of the seven items of model construction or model evaluation indicates that more students included this feature after the curriculum implementation than before the unit, though there is some variation in the extent of increase depending on the context and wording of each item. We note, however, that the pattern of increasingly using invisible objects and their movement was not found in responses to pre–post assessment items about model revision and use. This is likely due to the limitations of the assessment items that asked students about their general reflections about model revision rather than their own practice.

Analysis of the interview data indicates that four out of six students utilized invisible particles and their movement in using their models of evaporation and condensation to explain or predict related phenomena. For example, this interview excerpt shows how a student used these ideas in his reasoning.

Interviewer	Could you use your final model, either [of] the condensation or evaporation, to predict other phenomena? For example, a mirror fogging up when you're taking a hot shower?
Student	Yeah, because the water is hot so the condensation—the mirror would be colder than the water and the water would evaporate because warm water evaporates faster than cold water. So then the water molecules would spread out into the bathroom and usually you have the door closed so it wouldn't be able to get out so then it would just attach themselves to the mirror, which is colder.

The presence of "water molecules" and their "spreading out" and then "attaching themselves" allowed this student to explain the process and outcome of this related phenomenon. Analysis of students' models in their workbooks enabled us to trace the extent to which students included invisible objects in their models over time during the unit implementation. The result is shown in Fig. 9.2b. Outcomes indicate that for each topic (evaporation and then condensation) more students included this explanatory feature in their revised models. The results also indicate that when the topic shifted from evaporation to condensation, some students brought these ideas forward with them to the new context while the others did not.

What influenced students to increase this feature in their models? Analysis of student workbooks provides some indication. Figure 9.2b illustrates the change between students' initial and second models of evaporation (model 1 and model 2) as well as the change between their initial and second models of condensation (model 4 and model 5). In both of these contexts, students largely made their own decisions about what to include in these models unlike in teacher-guided consensus models (model 3 and model 6). Between their initial and second models, students engaged in empirical investigations and experienced computer simulations. Given that empirical investigations did not directly provide this feature, one can argue that many of these changes came from students' experience with the computer simulations. Figure 9.3 is an illustrative example of the change between one student's model 1 and model 2. Note that this student explained evaporation more effectively by utilizing invisible particles in his second model of evaporation. Additionally, students explicitly pointed out in their interviews that computer simulations had impacted their models. Two students' responses below illustrate this point.



First model of evaporation **Second model of evaporation**

Fig. 9.3 A student's initial and second models of evaporation

Interviewer ... [Were the computer simulations] helpful for you?

Student 1 Yeah.

Interviewer How?

Student 1 Because of the movement, like if there was a gas they would go fast and like...the molecules would do that. If it was a liquid it would be slow and it would spread apart. And a solid they would be stuck together and going slow in different directions.

Interviewer Did you think those simulations were helpful? Did you learn anything from them?

Student 2 Yeah, that there were molecules everywhere in the air. I just thought it was just air.

In summary, elementary students' increasing inclusion of invisible objects or, more specifically, invisible particles and their movement in modeling indicates the potential impact of the computer simulations in the MIS. Although there are many explanatory components of computer simulations, these features enabled students to appreciate and access the scientific explanation. In other words, students began to see the utility and power of explaining macroscopic phenomena using the theoretically constructed entities of invisible objects and their movement, rather than telling a narrative that involves objects and processes observable in everyday life.

The Influence of the Social Interactions in MIS: Students' Attention to Audience and Communicative Features of Models

Finally, we were interested in finding out how the social interactions included in MIS affected students' modeling practices. Analysis of the pre- and posttest data, students' models, and the interview data shows some evidence that students increasingly considered audience and communicative features of models in their modeling practices.

Analysis of the written assessment suggests that students generally became more attentive to communicative features of models such as labels in model construction and evaluation (Table 9.4C). Analysis of data from three items asking respondents to construct a model indicates that students increasingly included labels in their later models to make them easier to understand from pretest to posttest. Figure 9.4 illustrates this change. Note that this student labeled "water," "water in the air," and "evaporation" distinctively in the posttest whereas he did not include any labels in the pretest. Analysis of four items about model evaluation also shows that students increasingly attended to the extent to which models are easy for others to understand. While the manner in which each student attended to this communicative aspect varied—including labeling, detailed description, and symbols—they all recognized that models should communicate what they contain effectively to audience. The following excerpts illustrate some typical responses.

- "A strength in model B is that is very detailed because detail usually can help you understand better." (item 7 in the pretest)
- "Limitation: confusing. No words to explain anything. And the striped pattern doesn't help either; Strengths = labeling." (item 7 in the posttest)
- "The strengths are shows water bits going up with arrows shows water on the lid and in the container. Limitations is [sic] cannot tell necessary if arrows are water bits." (item 5 in the posttest)

The written assessment analysis indicates that few students displayed attention to communicative features in their response to the items of model revision and model use. The two items about model revision involving scientific and scientists' models did not indicate that students considered communicative effectiveness in revising models possibly because students seemed to think that scientific and scientists' models already hold enough communicative clarity. Further, the items of model use did not offer a context that required students to think of communicative features.

Analysis of student models in their workbooks produced the same pattern as the findings from the pre–post assessment analysis. Figure 9.2c shows that students

Fig. 9.4 A student's model in pre- and posttest (item 2)

increasingly included labels when they constructed and revised models. Note that a considerable number (26 out of 34 or 76%) of students transferred this feature as they entered a new topic (condensation). This evidence indicates that students became more aware of audience as they went through the unit.

The result of the interview analysis supports this analysis. Five out of six noted the communicative aspects of models for multiple questions about model evaluation. For example, one student mentioned helping others' better understand his model as one rationale for his model revision.

Interviewer	Okay. Is there any other reason for you to make the change?
Student	Yeah, because it explains more. I didn't really have any labels on this one (initial model of evaporation). So if this was in a museum, people who saw it wouldn't really understand it because it didn't have any labels or explain what happened to the water.

These results suggest that students increasingly attended to audience and the communicative features of models in constructing, revising, and evaluating models. Such evidence suggests the potential impact of the social interactions in MIS on student modeling. At the same time, we notice that few students adopted more advanced social features such as evidence-based argumentation from their experiences of peer evaluation and consensus model construction in MIS. Most students instead focused on basic communicative features of models such as labeling perhaps because this evaluation criterion was both accessible and acceptable within students' social norms. The results reported here may indicate a potentially important first step toward more sophisticated modeling practices.

Discussion and Concluding Remarks

In conclusion, the MIS seemed to have impacted students' modeling practices in several ways: First, empirical investigations allowed students to note the importance of empirical evidence and implicitly use this evidence in scientific modeling, although very few students explicitly illustrated evidence in their models. Second, the computer simulations enabled students to increasingly use invisible objects (particles and their movement) as an explanatory feature in their models. Lastly, students' engagement in social interactions such as peer evaluation and consensus model construction helped them become more aware of audience and communicative features of their models.

What do these findings indicate about approaches that can support rich modeling practices and the effectiveness of MIS? The success of the MIS-embedded unit depends on the objectives for students' modeling practices. On the one hand, few elementary students came to note and utilize the sophisticated epistemic relationship between empirical evidence and models, the power of mechanism as an explanatory feature, or the value of criteria-based peer evaluation and argumentation as a result of the implementation of the model-centered unit. On the other hand, the evidence indicates that the various features of MIS within this 6-week unit may have supported students in moving in that direction. These successes and opportunities for improvement provide ideas for further development and implementation of MIS in our design experiment work.

One aspect to consider further is how to most effectively weave together modeling practices and reflective MMK activities in MIS. The balance and timing of the practices and the discussion of reflective knowledge are critical. Engaging students in modeling practices without discussing the nature and purpose of models and modeling in which they are engaged might lead to acquisition of skills in a mechanistic sense and hinder students from generalizing and transferring their practices and knowledge to other contexts. On the other hand, incorporating multiple MMK discussion at the beginning of the unit can sometimes be overwhelming and abstract—appearing as additional information to passively learn. Some evidence from this research as well as those of others (Buckingham & Reiser, 2010; Kenyon, Cotterman, Todd, Reese, & Reese, 2010) indicates that students need to engage in modeling practices in multiple contexts to develop MMK. At the same time, we also have seen the value of relatively brief but relevant MMK discussion guided by teachers before, during, and after each MIS feature (e.g., empirical investigations). We theorize that a sophisticated integration of modeling practices and MMK activities in MIS over an extended period of time will likely promote students' meaningful engagement in scientific modeling.

A second aspect for further consideration is how to develop the social dimensions of MIS to make them more accessible for students. Our finding that students began to attend to basic communicative features of models without attending to criteria-based peer evaluation and argumentation leads the authors to think about the challenging nature of social dimension of scientific modeling. As previous research has shown (Berland & Reiser, 2009; Jiménez-Aleixandre et al., 2000), engaging students in scholarly social interactions can be difficult. This is an area in which students' everyday social norms take a strong hold, and shifts to new social norms can be challenging for students and teachers alike. Our work indicates that students need additional support for taking on intellectual roles as scientists to produce significant change. Prior work (e.g., Herrenkohl & Guerra, 1998) shows that retaining a participant structure that bears the characteristics of scientists' social interactions throughout the unit or across multiple contexts could make this aspect more accessible for students. In addition, we hypothesize that students' participation in constructing and applying evaluation criteria is critical for their effective use. In conjunction, students may use the criteria more effectively when scientific discourse is made explicit and is distinguished from daily discourse. An everyday meaning of evidence could be compared to the scientific meaning of evidence for helping students better understand why empirical evidence is an important evaluation criterion.

Finally, we note the important role of the teacher in mediating the implementation of MIS-embedded units and the need to explore this dimension further. Because modeling practice is a sociocultural phenomenon, the teachers played an important role as “culture brokers” (Aikenhead, 1996) or agents who know both scientific Discourse and student Discourse. The teachers in our work contributed and significantly impacted students’ uptake of scientific modeling. In particular, we found that the teachers linked students’ and scientific Discourses by utilizing a hybrid or blended instructional practice that contains both elements of school science practice and elements of authentic scientific inquiry (Schwarz, 2009). Incorporating an understanding of this hybridization into MIS and the professional work around its development and implementation will likely promote the impact of MIS on students’ modeling.

In this chapter we presented our approach to engaging elementary students in scientific modeling. Analysis of some of the empirical outcomes from using the MIS approach indicates that empirical investigations, computer simulations, and social interactions in MIS assisted students in developing an emergent sense of important features of models and modeling and in moving toward more sophisticated modeling practices. Overall, our analysis indicates that MIS has potential as a pedagogical approach for promoting students’ modeling practice and related knowledge. As an instructional tool, MIS includes extensive features that are important in mediating the students’ Discourse and the scientific Discourse. Such features should be combined with additional work to determine the nature and balance of modeling practices and MMK, the support of social dimensions in the practice, and the attendance to the teacher’s role as a culture broker in the practice. Further study and refinement of MIS along these lines may continue to help students engage and progress in this important scientific practice and gain proficient scientific literacy.

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Part III
Modeling and Teachers' Knowledge

Chapter 10
Relationships Between Elementary Teachers' Conceptions of Scientific Modeling and the Nature of Science

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Introduction

Though there is no single definition for scientific literacy, it has long been recommended that an understanding of aspects of nature of science (NOS) is an important component of scientific literacy (DeBoer, 2000). However, it has been found that teachers generally do not hold adequate understandings of NOS themselves (e.g., Akerson, Abd-El-Khalick, & Lederman, 2000; Lederman, 1992). Participation in long-term professional development programs has been found to improve teachers' understandings of NOS, their abilities to explicitly teach NOS in their own classroom settings, and to influence their students' understandings of NOS (Akerson & Hanuscin, 2005; Akerson, Hanson, & Cullen, 2007). As such, we are exploring the influence of a professional development program's influence on elementary teachers' conceptions of NOS as well as their understandings of scientific modeling and any connections between their understandings of these two constructs. Because scientific modeling can be used to develop NOS understandings, we thought it would be particularly interesting and informative to explore the relationships between their understandings of these two constructs, while helping teachers meet the Indiana Academic Standards. We are reporting the results of the second year of a professional development program. We have participants who have completed either one or both years of the program and can therefore report data from long- and short-term participants.

Our research in connection with this professional development program in Indiana seeks to improve elementary teachers' understandings of (a) nature of science (NOS), (b) scientific modeling, and (c) connections between their NOS views and understandings of scientific modeling. Our specific research question became "What is the relationship between teachers' views of nature of science and their views of scientific modeling?"

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_10,

Literature Review and Framework

Science education reform documents call for teachers to portray science as it is conducted by real scientists (National Resource Council, 1996; Roth, 1995). It is because most elementary science instruction is textbook driven and didactic and far removed from how scientists truly conduct science, and many students do not understand NOS (Bentley, 2003). NOS refers to the epistemology of science, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Lederman, 1992). Some important aspects of NOS have been advanced in recent reform documents including *Science for All Americans* (AAAS, 1990) and *National Science Education Standards* (NRC, 1996). These aspects are that scientific knowledge is (a) robust and tentative, (b) is partially socially constructed, (c) subjective or theory-laden, (d) developed through observation and inference, and (e) creates theories and laws.

Prior research has shown that elementary teachers and students often do not have appropriate views of NOS (Abd-El-Khalick & Akerson, 2004; Akerson & Abd-El-Khalick, 2003; Akerson & Abd-El-Khalick, 2005; Akerson et al., 2000; Gess-Newsome, 2002). Appropriate sustained professional development has been shown to improve teachers' views and practice (Akerson & Hanuscin, 2005; Akerson, Hanson, & Cullen, 2007). Before an elementary teacher can effectively implement inquiry-based science lessons, she must personally experience inquiry-based instruction. Preparing elementary teachers to use inquiry methods to teach science is difficult because many have not experienced this type of instruction themselves (Kielborn & Gilmer, 1999); they are confused about the meaning of inquiry, inadequate preparation in inquiry teaching methodology, and their belief that inquiry-based instruction is difficult to manage (Welch, Klopfer, & Aikenhead, 1981). For these reasons they are unlikely to include inquiry in their classrooms. One way to help them manage inquiry instruction is to connect it to the teaching of process skills to their students.

Scientific modeling is a higher order process skill that incorporates the following fundamental process skills used in scientific inquiry: observing, questioning, hypothesizing, predicting, collecting, analyzing data, and formulating conclusions. Because the use of scientific models is crucial to the scientific inquiry process, teachers must gain an understanding of the value of scientific models and modeling. According to the National Science Education Standards one of the "fundamental abilities of inquiry" is to "develop descriptions, explanations, and models using evidence" (National Resource Council, 1996). Indiana's academic standards require that students be able to use models at all levels of learning in grades K-6. The number system that follows refers to specific section numbers in the standards. The students should be able to compare and contrast objects (K.6.1) and describe the differences between models and the real phenomena represented. Models can also be used for learning about real-world objects, processes, or events (1.6.1, 2.2.1, 3.6.3), show how models can be used for the prediction of real events (4.6.3), and demonstrate how models represent real objects, events, and processes (5.5.3). The students should also be able to use models to illustrate processes that may otherwise not be observable in the classroom. Justi and Gilbert (2002) stated that in order to learn science, students should not only understand major scientific/historical models and their limitations but also have an adequate view of the nature of models. They go on to say that in order "to learn to do science, students should be able to create, express and test their own models" (p. 1274). Thus we intend to emphasize scientific inquiry through the use of scientific models to describe scientific ideas. Often the incorrect use of models can lead to student misconceptions. For example, fire has been used as a model for the sun; however, this can lead to misconceptions because as it turns out, nothing in the sun is burning (AAAS, 1990). Well-developed and used models offer excellent means to convey concepts that are either too small in scale, too abstract, or too complex for students to access directly (Gilbert, 1992).

Often textbook diagrams and pictures can be misleading (Anderson, 1990) simply because of the difficulty of representing three-dimensional events in two dimensions (Kane, 2004). In addition, research reveals that science students have a limited perception of the abstract scientific concepts represented by models; they only see models as concrete mini-representations of larger or smaller concrete concepts or objects. In other words they do not successfully use models to understand abstract concepts (Grosslight, Unger, Jay, & Smith, 1991). Unfortunately, teachers often share these misconceptions, which, in turn, facilitates this cycle of incorrect concept knowledge (Hashweh, 1987). Through the work in this professional development program the participants improved their views of the use of models for scientific understanding.

Educating teachers about the effective use of models is a priority if we are truly committed to helping students both to understand NOS in general and to grasp the utility as well as the limitations of models in specific. For teachers to effectively use models in the classroom, they must not only understand the connection between the scientific content and the model in question but also understand the student's perception of the model. Research tells us that teachers have a limited understanding of the use of models, and in many cases, their understanding includes many inconsistencies (Van Driel & Verloop, 2002, p. 1255). The principles that must be addressed to adequately prepare teachers in the use of scientific models in inquiry lessons include the following:

- Modeling requires extensive periods of time for practice and numerous different contexts for practicing modeling.
- The students' activities and the teachers' role should be in harmony with each other.
- Models should be used at appropriate times in the course of instruction.
- Models should be of appropriate type (Saari & Viiri, 2003, pp. 1346–1347).

Teacher professional development about the use of models should focus on allowing teachers to work in organized teams to design lessons focusing on models, implement those lessons in individual classrooms, and then revise those lessons based on the experiences of the teachers in the classrooms (Van Driel & Verloop, 2002). The professional development program we conducted and researched was entitled

Scientific Modeling for the Inquiring Teacher Network (SMIT'N) and through it we sought to prepare the teachers to help students develop models, formulate explanations, and evaluate data as described in the National Science Education Standards (NRC, 1996). These techniques engaged teachers mentally and physically and help them to develop a deeper understanding of the nature of scientific inquiry (Hitt & Townsend, 2004).

Method

We sought the answers to three questions in order to assess the effectiveness of the second 2-week summer program. First, what are the elementary teachers' understandings of the nature of science (NOS), pre/post? Second, what are the elementary teachers' understandings of scientific modeling, pre/post? Third, what are the connections, if any, between their NOS views and understandings of scientific modeling? We used an interpretive design with qualitative methodology to explore our research questions (Bogdan & Biklen, 2003). We describe our methodology in the sections below.

Participants

The participants included 19 K-6 teachers. Thirteen consented to participate in the research, and those are the participants included in this report. The teaching experience levels of the participants ranged from 1 to 25 years. There were 2 male and 11 female teachers in the research portion of the program. The teachers who participated in this study had a variety of experience with NOS and scientific modeling. Four were participating in their third year of a separate NOS-focused professional development program conducted by the first author, four were in their second year of the SMIT'N program, and seven were in their first year of the program. We compared their conceptions of NOS and scientific modeling to discern differences among levels of experience and levels of participation in the program. The study used qualitative data collection methods described below.

Intervention

The activities in the second summer institute of this 2-year professional development program were designed to provide instruction to teachers beyond the level of content understanding they are expected to teach to their students. These activities allowed the teachers to be involved in authentic biology scientific inquiry through which they were able to learn content beyond what they will teach. The teachers were engaged in classroom inquiries and fieldwork led by biology graduate students, as well as science education graduate students and faculty to help them understand biological science at levels above what is recommended by the Indiana Academic frameworks. The workshop facilitators modeled instruction in the inquiry process by having the participants engage in scientific inquiries about invasive plant species. This content and pedagogy were used to provide a model for them to translate their new understandings of content and inquiry instruction to their own classroom practice. This part of the professional development program focused on helping the teachers design their own scientific inquiry units to be used in their classrooms during the following school year. The science education faculty and graduate students led these pedagogy sessions. Having teachers work in grade-level teams during the scientific inquiries and on designing units also fostered teacher collaboration.

We used research-based approaches to the professional development (e.g., Bell & Gilbert, 1996; Loucks-Horsley, et al, 2003) to ensure that the best strategies were used to help teachers improve their practice. We aligned our activities to the core principles of professional development in the State of Indiana's Academic Standards ensuring a long-term, sustained professional development. The entire program spanned 2 years, with two 2-week summer workshops followed by two school year workshops each year, one in the fall and one in the spring. In addition we provided individualized on-site classroom support to teachers via biology graduate students and science education graduate students, who aided in teaching, planning, and providing materials to teachers. We also documented the effectiveness of our program through collection of data such as classroom observations, lesson plans, and interviews of the teachers as well as their students. We provided feedback to teachers during the follow-up sessions and the classroom visits based on the assessments and through the incorporation of teacher reflective practice. We continually adjusted our program based on classroom observations and documentation collected.

Our project was aligned with the Indiana Content Standards to ensure that during each of the summer and follow-up school year sessions, specific science content standards would be met. All activities are specific to teaching students about the seven modules within the living environment, including diversity of life, interdependence of life, human identity, evolution, and common themes. Common themes include models and scales, constancy, and change and systems. During the second summer workshop which is the focus of this study, the program was divided into morning and afternoon sessions. The morning sessions emphasized developing teachers' content knowledge of biology through inquiry-oriented experiences that emphasized modeling, and the afternoon session consisted of the teachers designing and carrying out an authentic inquiry related to invasive plants.

During the morning sessions facilitators led the teachers through investigations in the classroom that helped them understand the content related to invasive plants, such as how to identify invasive plants and why certain plants are classified as invasive. Guest speakers from local agencies that deal with invasive plants were employed to provide supplementary content background. Each morning teachers were treated to examples of scientific models and the importance of scientific models in representing scientific knowledge. We connected these examples to the content they were learning in the morning and also provided examples of pedagogy for their own classrooms. Scientific modeling was emphasized throughout the workshop beginning with the first day when a discussion ensued regarding defining scientific modeling as "an abstract, graphical, conceptual, or mathematical model of reality that is generated to represent a scientific phenomenon" (Van Driel & Verloop, 2002). On the second day of the workshop teachers explored a model of the atom using the bean model from the "Dry Ice Investigations" GEMS book (Barber, Beals, & Bergman, 1999). On the third day of the workshop teachers explored a model of transpiration using observations of leaves under different circumstances (water, water and heat, water and light) and developed inferences from their observations. Day 4 required teachers to build models of flowers and the process of germination after making observations of flowers and reading about germination. On day 5 the teachers engaged in a modeling activity where they used play-dough to represent the dissolving of M & M's in water (the previous investigation). This modeling activity led to a discussion of how scientists developed models of molecules.

During the sixth day, which was the second week of the workshop, teachers explored the health of a river on campus, the Jordan River, by checking water quality, observing life forms, and conducting a survey of observable pollutants (litter). After their investigation they explored a model of a river back in the classroom and thought about the following questions "How is the model like the target (river)? How is it different from the actual stream? What misconceptions could arise from this model? and "How can we improve this model?" On the seventh day teachers built models of a human and pig cells using cookies. During this activity they were required to make continuous modifications to their models to make them more realistic to the target. Day 8 treated teachers to models in the form of mathematical formulas as they explored Newton's Law $F = ma$ through a car competition. Teachers built and conducted investigations of model cars and were able to modify their designs as they tested them. Following their testing teachers discussed how their models were different from reality, misconceptions that could arise from the use of the model car, and ways to modify their design to make it even more realistic. In the final 2 days the teachers were required to design scientific models as part of their invasive plan investigations. They were also required to include elements of scientific modeling in the units they designed as part of the workshop so that they could teach scientific modeling to their students in the following school year.

In the afternoons teachers were provided with instruction on developing an authentic inquiry—the kinds of questions to raise that could be answered in a week long investigation and approaches to investigating, such as using transect surveys to sample plots of invasive plants. As part of their culminating research, they were to explore ways to design a model of the environment they were researching regarding invasive plants. Teachers worked in grade-level groups to design their inquiries and conducted their scientific inquiries at their school sites to enable them to plan similar investigations with their own elementary students. Teachers conducted their investigations during the afternoons of the workshop, analyzed their data, and presented their results on the final day of the workshop. Teachers also designed a multiday inquiry lesson plan that included scientific modeling they could then use with their own students.

Data Collection

All participants' conceptions of the target aspects of NOS were assessed pre and post using the views of nature of science questionnaire form VNOS-B (views of nature of science version B) (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). Thirty percent of the participants were selected for interview prior to their participation in the workshop and at the conclusion of the workshop. These interviews allowed participants to elaborate on their views and enabled us to validate our interpretation of teachers' written responses. These interviews were audiotaped and transcribed for later analysis. To assess change in views of scientific modeling, an adapted open-ended interview version of Van Driel and Verloop's (1999) scientific modeling survey was used (see Appendix for a copy of the survey). The interview protocol was modified to apply to models in general rather than being tailored specifically to secondary chemistry teachers. The survey was changed to an interview protocol by identifying categories from the original and formed into general questions so that the teachers could more easily elaborate their responses.

Field notes were made of daily content and pedagogy sessions during the summer workshops. These notes were reviewed at the end of the workshop and were used to ensure that explicit reflective NOS instruction took place and to determine how teachers reflected on their views of NOS and scientific modeling while interacting with one another.

Data Analysis

Data analysis focused on comparing pre- and post-instruments from the workshop. Each researcher independently analyzed interview transcripts and questionnaires. Pre-instruction interview transcripts and corresponding VNOS-B questionnaires were separately analyzed to generate profiles of each participant's NOS views. To describe the participant's initial level of understanding a response was marked with a + if it was determined that the participant held an informed or full understanding with examples when asked to provide them. If their answers showed an adequate understanding a √was used and an inadequate viewed showing no understanding was coded with a –. The independently generated profiles were then compared to ensure the validity of the questionnaire. The same process was followed for the post-instruction interviews and questionnaires. After this initial round of analysis the results were compared by the researchers and it was then decided in order to eliminate the differences in coding two additional codes would be used. A √+ was used to code a response that was determined to be adequate but did not display full understanding or provide examples; a √– was used if the participant did not provided good examples or descriptions. After the second round of analysis, the generated summaries for all participants were searched for patterns or categories. Discrepancies in coding led to researchers' discussions, which resolved any conflicts in interpretations. The categories of the participants' understandings of NOS and inquiry were checked for confirmatory or otherwise contradictory evidence in the data and were modified accordingly. Several rounds of coding, confirmation, and modification were conducted to satisfactorily reduce and organize the data.

With respect to the modeling interview, we reviewed the responses for patterns. We then compared the teachers' views of NOS to their modeling views to discern any relationships. We also sought patterns of differences among participants who were new to the program and those who had participated for 2 years.

Results

In the sections below we will present the results of our study. First, we will describe teachers' views of NOS aspects as a result of participating in the professional development program. Next, we will describe teachers' conceptions of scientific models, followed by a discussion of the relationship they see between scientific modeling and aspects of NOS. We will use descriptions of classroom practice to illustrate how they have taught NOS embedded within scientific modeling.

Teachers' Conceptions of NOS Aspects

Prior to participating in the workshop the new teachers held mostly inadequate views of all NOS aspects. For instance, one teacher stated of the relationship between theory and law "Theories are weak knowledge. When there is more evidence they will become laws, or just get thrown out." This statement also illustrates an inadequate view of the tentative NOS. However, one of the returning teachers said, "Theories are constantly being adjusted and fine-tuned as new evidence is gathered and more people are involved in exploring them. We teach theories because they are the best explanations that we have at the moment and are based on years of research. They are certainly not just guesses." There were similar differences in conceptions of all NOS aspects, with new teachers holding more misconceptions than returning teachers or teachers who had participated in a prior NOS professional development program (PPD teachers). See Table 10.1 for differences in conceptions pre-instruction across participants.

Post-workshop questionnaires and interviews showed improved conceptions of NOS. For example, all seven new teachers held adequate conceptions of the tentative NOS at the conclusion of the workshop. These teachers held the view that "science can change with more evidence." Three of the returning teachers and all of the PPD teachers held informed conceptions of NOS, with the idea that "scientists might change their claims if they collect more data or if they look at the existing data in a different way."

Similarly, after the workshop all seven new teachers held adequate conceptions of the distinction between observation and inference, describing the relationship as "scientists take observations, then describe what they mean, and those are their inferences." All returning and PPD teachers held informed conceptions of observation and inferences post-instruction, stating that "scientists collect data, make observations of the data, interpret the data through their own background

Table 10.1 Participants' pre-instruction NOS conceptions

NOS aspect	New teachers	Returning teachers	Prior professional development teachers
Tentativeness	Inadequate = 3 Adequate = 4 Informed = 0	Inadequate = 0 Adequate = 4 Informed = 0	Inadequate = 0 Adequate = 1 Informed = 3
Observation and inference	Inadequate = 3 Adequate = 4 Informed = 0	Inadequate = 0 Adequate = 4 Informed = 0	Inadequate = 0 Adequate = 2 Informed = 2
Theory and law	Inadequate = 6 Adequate = 1 Informed = 0	Inadequate = 0 Adequate = 4 Informed = 0	Inadequate = 0 Adequate = 4 Informed = 0
Empirical	Inadequate = 6 Adequate = 1 Informed = 0	Inadequate = 0 Adequate = 3 Informed = 1	Inadequate = 0 Adequate = 1 Informed = 3
Creativity and imagination	Inadequate = 2 Adequate = 5 Informed = 0	Inadequate = 0 Adequate = 3 Informed = 1	Inadequate = 0 Adequate = 3 Informed = 1
Subjectivity/ sociocultural	Inadequate = 2 Adequate = 2 Informed = 0	Inadequate = 0 Adequate = 4 Informed = 1	Inadequate = 0 Adequate = 4 Informed = 0

knowledge and viewpoints, and infer the meaning of the data." No longer did any teacher make the claim that scientists had to actually see something to interpret the data, recognizing that scientists could make observations of indirect data (not accessible through the five senses) and infer an explanation (e.g., for when they developed a model of the atom, no longer did teachers think they actually saw the atom through a microscope).

Regarding the relationship between scientific theories and laws, no longer did any teacher state that theories would become laws, rather all teachers held an adequate view of the relationship between theories and laws. For example, one new participant stated, "Yes, theories change. Theories and laws have different jobs. The laws are statements of patterns and regularities in the natural world. Theories are explanations for those patterns." This statement indicates an appropriate understanding of theories and laws as separate and evidence-based kinds of scientific knowledge. The returning teachers from SMIT'N continued to hold improved views of theory and law.

Teachers' conceptions of the empirical NOS were also improved. For example, all new and returning teachers held at least adequate views of the empirical NOS, with one of the returning teachers and all of the PPD teachers holding informed views. One returning teacher illustrated her informed view through her statement "Scientists use data to develop theories and laws to explain occurrences and situations based on their current knowledge." One new teacher's statement "Scientists use observation of data to make claims" illustrates her adequate view.

Teachers also improved in their conceptions of the creative and imagination NOS as a result of participating in the program. At the conclusion of the program none of the teachers held inadequate conceptions, and two of the returning and all of the PPD teachers held informed conceptions. An example of an informed conception is illustrated by a PPD teacher who stated “Scientists create ideas and understandings that are influenced by society and their culture. Scientists make tentative claims from their data, and might change their ideas as they are thinking creatively about that data.” One new teacher illustrated her improved view from an inadequate to adequate view in her statement “Yes, scientists are creative when they think about the conclusions they draw from the data they collect.”

Regarding the subjective and sociocultural NOS, all new teachers held adequate conceptions after the workshop, with two of the returning and three of the PPD teachers holding adequate conceptions and two of the returning and one of the PPD teachers holding informed conceptions. For example, one returning teacher showed her informed conception by stating “Scientists bring their personal experiences and biases to their observations just like the rest of us. Personal and cultural experiences, as well as prior knowledge can influence the way a scientists, or any person, looks at the world.” One new teacher’s statement illustrated her adequate view as she said “They have different scientific opinions and interpret the data differently.”

Teachers’ Conceptions of Scientific Models and Relationships of Scientific Models and NOS Aspects

When comparing the differences in the open-ended statements on the pre- and post-surveys, a few items stood out as showing a descriptive change regarding teachers’ perceptions of models. Six of the new teachers improved their views of scientific modeling as illustrated by their responses to “How would you describe a scientific model?” and “How do you think scientists use models?” For example, post-workshop, one new teacher stated that a scientific model was “a picture, a map, a 3D representation of scientific theory,” while her pre-workshop statement was simply “a model helps the viewer connect information.” One can see that there was an improvement in describing a scientific model, although the teacher did not include in the description that a mathematical formula could be a model. Returning teachers held adequate views of modeling pre-instruction for this year. All of the teachers describe scientists using models to help them develop theories, plan investigations, make explanations, develop solutions, test ideas, and explore their thoughts regarding scientific claims. One teacher stated “We do a lot of modeling in our science class, to show how scientists do their work. We made biomes in a bottle, we did some modeling with lentils and dandelions, and we have used some mathematical models. We have changed the way we teach.” Another teacher said “Scientists use models just the way we do—to figure out things, explain things, to move things—even ideas—around. To think about what they are thinking about. It helps them change their ideas if they need to. Which really is part of the tentative nature of science.”

Indeed, all teachers also realized that scientific models were not exact replicas of reality but were representations that enabled scientists to understand and explain phenomena. Two teachers also described models as a way to represent things that were too small or too large to conceptualize or see, such as an atom or the solar system. For example, one teacher said "Well, of course we can't see an atom and we can't really go out into space to make a map. Scientists use models to help us, and themselves, understand things too small or too large to really see." Teachers also recognized that scientists used models to describe most of the phenomena they study, such as principles (Newton's laws), organisms, and systems. One teacher stated "They can represent really anything a scientist is exploring, like ecosystems, organisms, whatever they are exploring. All scientists use models."

Regarding the connection of scientific modeling to understanding NOS aspects we found interesting patterns of understandings. For example, the post-VNOS-B responses showed that teachers began to contextualize their responses to scientists' representations of atoms as building models. For instance, one participant stated, "We can't see atoms. Scientists are fairly sure [of what they look like] because of the way elements react to each other. The conceptual model seems to explain in a consistent way these reactions."

Teachers described emphasizing scientific modeling and NOS in their instruction, and in fact, we observed teachers doing just that. One new first-grade teacher adapted a lesson in her FOSS Plant Kit to enable students to "see" how bees pollinate a plant. Instead of doing the "pollination" herself, as a demonstration, she provided students with cotton swabs and they enacted the pollination themselves, serving as models of bees and other insects that may pollinate plants. She spoke with the students about how they were using a scientific model for how bees pollinate plants.

Two fourth-grade teachers described how they developed a model for conceptualizing standard measurement by giving students straws to use as measuring devices to measure the length of their desks. However, unbeknownst to the students, the straws are different lengths and cause students to wonder why their measurements are different. The teachers stated "We consider the straws to be models. It's a model to show that you need a standard unit of measurement, and if we don't have one we all end up with different answers."

A new sixth-grade teacher taught a series of lessons on roller coasters through which she used student-built models of roller coasters to explore ideas of force and motion and simple machines. She also partnered her class with a second-grade teacher, and the teams of classes built models of biomes in soda bottles that they then observed over the course of the semester. They thought that students would be able to see how different organisms in a biome would interact using this model.

All teachers noted the same relationships between NOS aspects and the use of scientific modeling. However, the new teachers needed to be prompted to remember the NOS aspects—we needed to provide them with a sheet that listed the target NOS aspects and then they could easily see the same relationships that the returning and PPD teachers saw. In essence, they described how all the NOS aspects were related to scientific modeling. One of the first-grade teachers stated "In the development of scientific models there will always be a part that is subjective because the scientist's previous knowledge and experience influences the development and vision of that model." All other teachers shared this same view.

Eight teachers also described how scientific tentativeness could be illustrated through scientific models through the designing and redesigning of models as data is looked at and looked at again. One teacher stated "I know science is tentative, and I can see that models are tentative representations of that knowledge. It is not like the knowledge isn't there, it is just that the models will change as the scientific explanation changes—the scientist may make a new model that fits the data better, or adjust the current model to make a better representation."

Four teachers also highlighted the use of models as related to the relationship of theory and law. Oftentimes scientists use formulas to represent a law, and the teachers recognized that these mathematical formulas were a type of scientific model. One sixth-grade teacher stated "It is like Newton's Laws, or the law of gravity. A mathematical formula can be used as a model to describe the relationships present in these principles. It is unlikely that these formulas will change, but they could if they find an instance where the formula does not work and needs to be tweaked."

Similarly, all teachers noted the use of observation and inference in the development of scientific models. One fourth-grade teacher said "Observation and inference is definitely connected to the development of scientific models. Scientists make observations of lots of data, and put that data together in a way that explains what they are looking at—that putting together of the data into a model is an inference of what is going on. They oftentimes need to make new inferences as they adjust the model while looking at the data."

Teachers also saw the development of scientific models as connected to scientific creativity and imagination, all connected to the collection of empirical data. For example, one second-grade teacher said "Models are the perfect illustration of creativity. Scientists are creating a representation of something they have noticed from evidence they collected." Another fourth-grade teacher stated "Scientific models are scientifically creative. Scientists have to imagine what the data means, and how to put together a representation of it to do further explorations, and also to share their ideas with other people—to help others understand the phenomena. And scientists from different cultures may create different models."

Implications

Our data analysis indicates that professional development with scientific inquiry and modeling as the central theme can be effective in providing immediate positive influence on teachers' views of NOS and that there are relationships between teachers' views of modeling and NOS. The sustained professional development program also supported teachers who had previously participated in NOS professional development and teachers who had participated in SMIT'N for one prior year. The program also capitalized on the knowledge provided by these teachers in helping to support the new teachers and their developing conceptions of NOS and scientific modeling. The returning teachers held fairly good views of NOS and modeling prior to the workshop, but their participation in the authentic inquiry helped to solidify and improve those views and allowed them to see how scientists conducted their own investigations. In addition, although new teachers needed prompting to recall all NOS aspects targeted in instruction, they were able to conceptualize and define these aspects at the request of the facilitators. All teachers were able to connect scientific modeling to all NOS aspects, though new teachers needed to be reminded of the NOS aspects. All teachers were also able to provide examples of NOS and scientific modeling to illustrate their understandings.

The facilitators did not make direct connections between scientific modeling and NOS aspects in the workshops, rather they drew the teachers' attention to the connections simply through asking teachers to describe connections they noted. This explicit drawing of attention required the teachers to reflect about scientific modeling as well as NOS aspects and draw connections themselves. Requesting the teachers to make the connections themselves is similar to the explicit instruction used to initially improve their conceptions of NOS (Akerson et al., 2000). Indeed, teachers were able to describe uses for models in line with what Gilbert (1995) recommended regarding conveying concepts too small or large in scale, too abstract, or too complex and also noted that models are not exact replicas and could be misleading (Anderson, 1990; Kane, 2004). They recognized this difficulty as part of the very nature of science itself—that it is impossible to make an exact replica of "reality" given scientists do not actually "know reality" and that scientific claims can change (tentativeness) due to subjectivity, reinterpreting empirical data, and further scientific creativity. Teachers did not see this inability of models to represent actual "reality" as a weakness, but rather as a depiction of the very nature of science itself. Therefore, we believe that the use of scientific modeling as a context for exploring both scientific modeling and NOS is fruitful when considering future professional development programs. Our method of embedding explicit discourse surrounding scientific modeling and NOS that was connected to the content they explored, and the inquiries in which they were engaged was successful in improving these teachers' NOS conceptions, conceptions of scientific modeling, and the connections they saw between scientific modeling and NOS.

Recommendations

Regarding developing future professional development programs that combine scientific modeling and NOS, we have several recommendations that fall from our results. First, we found that instruction about scientific modeling is important so that teachers can recognize (a) what it is, (b) its uses in the scientific community and for teaching, and (c) examples of scientific modeling. Indeed, a good portion of our 2-week intensive summer workshop focused on these broad ideas, within the context of teachers developing and carrying out an authentic inquiry on invasive plant species, as well as designing science units that would incorporate scientific modeling for their own students. This explicit instruction in scientific modeling helped the teachers understand how scientists use modeling and how they could teach scientific modeling to their students.

Second, an emphasis on NOS is important to help teachers conceptualize the aspects that are targeted in the program. However, we did not specifically teach the NOS aspects in this summer as we had done in the previous summer, mainly because we had so many returning teachers. Instead, we used the guided inquiries as well as the authentic inquiry on invasive plants to emphasize the NOS aspects we had previously targeted the previous year of the SMIT'N program. The connections we were able to make with the inquiry activities of this summer to the activities in the previous year helped to solidify and improve the NOS conceptions of the returning teachers and also improved the new teachers NOS conceptions to at least an adequate understanding of the target aspects. Indeed, this type of instruction enabled all teachers to recognize relationships and connections between scientific modeling and NOS aspects.

Third, as do others (e.g., Bell & Gilbert, 1996; Loucks-Horsley et al., 2003), we recommend sustained professional development programs to help teachers to initially change and improve their conceptions of NOS and scientific modeling and then to develop teaching strategies for their own classroom practice. We have found that teachers are generally surprised about their new ideas about science and then require some time and support to think about how to teach these ideas to students, particularly if their curriculum does not support such instruction. The relationship between practical teaching experience and theoretical background for understanding NOS is not linear, and teachers require support in translating their new NOS understandings into classroom practice (Akerson, Cullen, & Hanson, 2009). In most cases elementary science curricula will need to be adapted by elementary teachers to include NOS and scientific modeling, and teachers need support in doing such adaptation, at least initially. Sustained support will help ensure that teachers' new conceptions are reinforced and that they are able to translate their new ideas into classroom practice to make impact on their students' conceptions of NOS and scientific modeling.

Appendix

Name: ______________________ Date: ______________

Thank you for your time in participating in this *Views of Scientific Models* interview. Your participation is greatly appreciated.

Years of teaching experience: ________________________

Grade level: ______________________________________

Please tell us what science classes you took in high school and college.

1. How would you describe a scientific model?
2. How do you think scientists use models?
3. What is the relationship between a model and its target (reality)?
4. What is (are) the purpose(s) of a(n) effective model(s)?
5. What are some things models can represent?
6. In what ways have you used models in your classroom this year?
7. What are some ways you would consider using models in the future?
8. Do you point out the use of models specifically with students?
9. How does the use of scientific modeling in the classroom fit into the overall use of scientific process skills?
10. Can models be used to support inquiry in the classroom? How? Or Why not?
11. How do you see models fitting into the learning cycle?
12. Do you see any links between the nature of science and the use of models?

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Chapter 11
Science Teachers' Knowledge About Learning and Teaching Models and Modeling in Public Understanding of Science

Ineke Henze and Jan H. van Driel

Introduction

About 10 years ago, science teachers in Dutch upper secondary education have begun teaching the syllabus of a new course entitled 'Public Understanding of Science' (PUSc). A distinctive element in this new syllabus is the critical reflection on scientific knowledge and procedures (De Vos & Reiding, 1999). In this respect, the introduction of PUSc is close to the vision on science education reform in many other countries, which requires students to become knowledgeable in varied aspects of scientific inquiry and the nature of science (cf. Crawford, 2007; Windschitl, Thompson, & Braaten, 2008). The implementation of PUSc coincides with a broad revision of secondary education in the Netherlands. Among other things, the purpose of this innovation is to stimulate self-regulated learning and to decrease the emphasis on teacher-directed education. Science teachers, therefore, are not only confronted with a new syllabus and new content, but also expected to adopt new pedagogical approaches, such as guiding and supervising students' learning processes rather than lecturing, as well as the use of new media. These ideas correspond closely to current international educational innovations that are designed, among other things, to help students develop a rich understanding of important content, think critically, synthesize information, and leave school equipped to be responsible citizens and lifelong learners (Putnam et al., 1997).

Aim of the Study

We know from previous research that teachers' knowledge of learning and teaching determines largely how teachers teach. It is the teachers' knowledge and beliefs or cognitive structures—also referred to as 'teacher knowledge' (Verloop, Van Driel, & Meijer, 2001), the 'personal construct system' (Kelly, 1955), and 'interior images of the world' (Senge, 1992)—that give coherence to experiences, thoughts, feelings,

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_11,

and actions, in a specific context. The development of teachers' knowledge has been found to be highly implicit (i.e., teachers are unaware they are learning) and reactive (teachers learn in reaction to events) and can be understood as 'workplace learning' or 'professional development' (Eraut, 2000; Schön, 1987). This process is greatly influenced by subjective factors on the one hand and by perceptions of task factors and work environment factors on the other (Klaassen, Beijaard, & Kelchtermans, 1999).

Shulman (1986) proposed that teachers' (professional) knowledge is comprised of a variety of categories, with one of these categories being pedagogical content knowledge (PCK). This category of teacher knowledge is specifically related to the subjects teachers teach. Shulman conceptualized PCK as including 'the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others' (1986, p. 9). PCK also includes 'an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons' (1986, p. 9). The development of PCK is rooted in classroom practice, implying that experienced teachers have stronger or more sophisticated PCK than beginners (cf. Clermont, Borko, & Krajcik, 1994).

In this chapter, we report on the method and results of a qualitative study of a group of Dutch science teachers, examining the first years in which they taught a new course on Public Understanding of Science (PUSc). We investigated the development in the teachers' comprehension concerning learning and teaching of one of the elements most characteristic of the new syllabus, that is, reflection on the nature of science. Previous research (e.g., Gallagher, 1991) has led to the general conclusion that science teachers possess limited knowledge of the history and philosophy of science. Consequently, their understanding of the nature of science is unsatisfactory. Furthermore, the relationship of this understanding to classroom practice has been found to be complex (Abd-El-Khalik, & BouJouade, 1997; Lederman, 1992). As the role of models and modeling in science is widely recognized as central in understanding the nature of science, this study specifically focused on the development of the teachers' knowledge of learning and teaching models and modeling in the context of the introduction of PUSc. To this end, we explored their personal knowledge about different educational activities focusing on models and modeling in the new syllabus and their pedagogical content knowledge of a specific topic in the syllabus, namely, Models of the Solar System and the Universe. We did not intend to describe in detail the particular knowledge (development) of individual participants, but, as people share similarities as well as differences (Kelly, 1955), we looked for parallels in the knowledge of different teachers in the study (cf. Meijer, Verloop, & Beijaard, 1999).

Public Understanding of Science (PUSc)

In 1999, a new syllabus on Public Understanding of Science was introduced alongside the traditional science subjects, such as physics, chemistry, and biology *for* *all students* in secondary education in the Netherlands. The program (curriculum) of this new syllabus is divided into six domains, A–F (SLO Voorlichtingsbrochure ANW, 1996). General skills (Domain A), such as language skills, computer skills, and research skills, should be developed in combination with the learning of specific subject matter that is introduced in relevant context issues of Life, Biosphere, Matter, and Solar System and Universe (i.e., Domains C–F). The development of students' capacity to reflect critically on scientific knowledge and procedures (Domain B) requires them to become able, among other things, to explain how scientists obtain a specific kind of knowledge which (by its very nature) is always limited and context bound, and how observation, theory formation, and technology are influenced by each other as well as by cultural, economic, and political factors. Students' reflection on scientific knowledge and procedures should be linked to specific science topics, for example, 'Health care' (Domain C: Life), 'The Earth climate (Domain D: Biosphere), 'Radiation risks' (Domain E: Matter), and 'Understanding the Universe' (Domain F: Solar System and Universe).

The Dutch upper secondary education system includes two different levels: general senior education (HAVO; Grades 10, 11) and pre-university education (VWO; Grades 10, 11, 12). In addition, students can choose between the streams of 'science and technology' and 'humankind and society.' The latter choice means that students drop the science subjects of physics, chemistry, and biology after Grade 9. Both streams (HAVO and VWO) have somewhat different emphases in their examination programs. The program for general senior secondary education (HAVO) places more emphasis on practical and concrete applications of the subject matter, whereas pre-university education (VWO) has more abstract and complex goals: pre-university students, for instance, should be capable of using their knowledge and skills in new situations or contexts.

Models and Modeling in Public Understanding of Science

Aiming to improve the comprehensive nature of students' understanding of the main processes and products of science, Hodson (1992) proposed three purposes for science education: (i) to learn science—that is, to understand the ideas produced by science (concepts, models, and theories); (ii) to learn about science—that is, to understand important issues in the philosophy, history, and methodology of science; and (iii) to learn how to do science—that is, to be able to take part in those activities that lead to the acquisition of scientific knowledge. In general, all natural sciences can be thought of as an attempt to model nature in order to understand and explain phenomena. Models and modeling are, as a consequence, applied and used extensively by natural scientists. Therefore, the achievement of Hodson's goals of a comprehensive understanding of science by the student entails a central role for models and modeling in science education (Justi & Gilbert, 2002). This is why, as it is expressed in Table 11.1, PUSc offers an appropriate framework to help students gain a rich understanding of scientific knowledge and procedures. To this end, the learning of scientific models (Domains C–F) and the act of modeling, that is, the production and revision of models (Domain A), should go hand in hand with the

Table 11.1 PUSc as a framework to improve students' understanding of science

	PUSc domains		
	A	C–F	B
Hodson (1992)	Learn how to do science	Learn science	Learn about science
Justi and Gilbert (2002)	Learn to produce and revise models	Learn the major models	Learn the nature of models

development of the capacity to make informed judgments on the role and nature of models in science (Domain B).

Teaching students about scientific models requires that teachers possess a robust understanding of the purposes, tentativeness, and power of science's products (Crawford & Cullin, 2003). Empirical research, however, suggests that both in-service and prospective science teachers possess uniformed and/or alternative views, in particular, of the role of models and modeling in science (Harrison, 2001; Justi & Gilbert, 2002; van Driel & Verloop, 1999). With regard to science teachers' knowledge of and attitudes toward the use of models and modeling in learning science, Justi and Gilbert (2002) concluded from a study of Brazilian science teachers that the teachers generally showed an awareness of the value of models in the learning of science, but not of their value in learning about science. Furthermore, modeling as an activity by students would not seem to be widely practiced. De Jong, van Driel, and Verloop (2005) explored Dutch pre-service science teachers' pedagogical content knowledge of models and modeling. The research findings indicated, among other things, that a majority of the teachers intended to pay attention to models as constructs, invented by scientists, but in their teaching practice appeared to have discussed models as objects or facts that are given. As a similar discrepancy has also been found among experienced teachers (Koulaidis & Ogborn, 1989), De Jong et al. (2005) suggested that pre-service and experienced teachers generally lack sufficient knowledge of strategies for teaching models as constructs. "This should be no surprise to anyone who has analyzed science curricula and textbooks, which are heavily stanced toward an entirely empirical and positivist epistemology" (Niaz, 2009, p. 45). Many science textbooks present a simplistic view of the origin and development of scientific knowledge. It is generally not made clear to students that theories and models are designed with particular purposes in mind (cf. Gilbert, 1991) and are subject to growth (Hodson, 1992).

The introduction of PUSc, including a move toward constructivist teaching strategies (in which models are used as cognitive tools to promote students' thinking), has introduced experienced science teachers to new ideas and topics that may influence their knowledge about learning and teaching models and modeling in science. With this in mind, we formulated the following general research question:

'How can the content and the development of experienced science teachers' knowledge of learning and teaching models and modeling be typified in the first few years of teaching a new syllabus on PUSc?'

Method and Procedure

Much of (science) teachers' knowledge of practice is tacit (cf. Korthagen & Kessels, 1999). Accessing such knowledge has proved to be exceptionally difficult as there exists a distinct inability to easily recognize, document, and articulate this knowledge in explicit ways (van Driel, Verloop, & de Vos, 1998).

Furthermore, the development of this knowledge is multifaceted and not linear (cf. Veal & MaKinster, 2010) and therefore hard to capture and portray. Because of this complexity, Kagan (1990) called for multi-method designs for investigating teachers' knowledge and beliefs, which focus on specific well-defined aspects. With this in mind, we formulated in our study on science teachers' knowledge of learning and teaching models and modeling two specific questions to be answered:

1. How can the content and development of experienced science teachers' personal knowledge of educational activities concerning models and modeling in PUSc be typified in the first few years of teaching the new syllabus?
2. How can the content and development of experienced science teachers' pedagogical content knowledge (PCK) of models and modeling concerning a specific topic in PUSc be typified in the first few years of teaching the new syllabus?

We used George Kelly's (1955) Repertory Grid technique to explore the teachers' personal knowledge (personal construct system) about educational activities corresponding to our interpretation of the three main aims of PUSc (Table 11.1). In addition, we applied a semi-structured interview to examine the teachers' pedagogical content knowledge of a specific topic in the syllabus, namely, Models of the Solar System and the Universe (Domain F in the PUSc curriculum, Fig. 11.1).

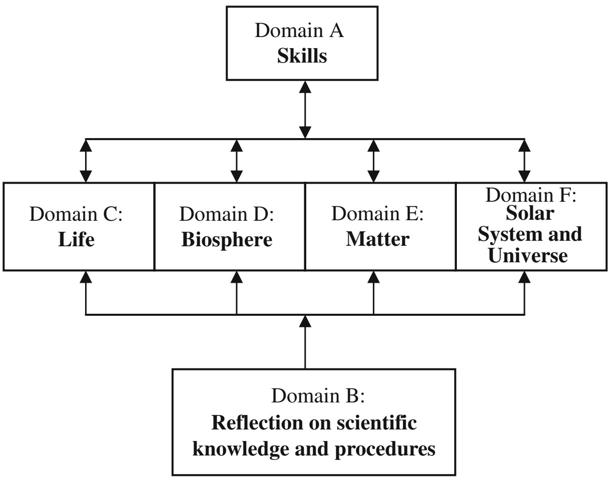

Fig. 11.1 Relations between program domains in PUSc

In the following sections we describe the participants of the study, the developed instruments, and the research procedure followed.

Participants in the Study

This study was conducted among nine PUSc teachers working at five different schools. All were using a teaching method called 'ANtWoord' ('Answer') which we selected for our study because of its emphasis on the role and nature of scientific models. It should be noted that in the Netherlands, schoolbooks are published by private publishing companies that operate outside the control of government institutions. Although books normally comply with the goals set by The Ministry of Education, the actual content of the books is not prescribed and there is considerable variation among authors. In other PUSc teaching methods, in contrast to ANtWoord, scientific models and the act of modeling do not receive as much attention. The nine teachers replied to a written invitation which we sent to the users of ANtWoord. After meetings at their schools, organized to explain the purposes and conditions of the study, they all agreed to join in. The teachers, all male, varied with regard to their disciplinary backgrounds and years of teaching experience. Among the participants were three teachers of physics, three teachers of chemistry, and three teachers whose original discipline was biology. Their teaching experiences in their own disciplines ranged from 8 to 26 years at the start of the study (2002). To become qualified to teach the new science subject, the teachers had taken part in a 1-year course, which was conducted nationwide. They were all among the first PUSc teachers at their schools.

The Repertory Grid Instrument

The 'rep grid' is essentially a matrix comprising a set of 'elements' and a set of 'constructs.' The elements comprise people, situations, or events, which are comparable and should span the area of the problem under investigation (for instance, all trips abroad in the last 5 years). The way that we make sense of these elements is represented by our personal constructs. The constructs may be thought of as bipolar, that is, they may be defined in terms of polar adjectives (good–bad) or polar phrases (makes me feel happy–makes me feel sad). As such, Kelly (1955) maintained that our discrimination of the world unavoidably involves contrast. When we characterize something in some particular manner, we are also indicating what it is not (for example, fat is only meaningful in relation to thin, large relative to small, or acid to alkali). These meaningful constructions of elements are working hypotheses which are put to the test of experience rather than being facts of nature.

The instrument developed for the present study can be characterized as a 'standardized' rep grid, consisting of provided elements and constructs (Corporaal, 1991). This allowed us to compare the teachers at two different moments in time, both as a group and as individually. To study the teachers' personal knowledge of teaching models and modeling, 12 concrete educational activities focusing on

Table 11.2 Rep grid elements (educational activities)

	Educational activity	PUSc domain	Aim for teaching science
I	You give, for students, concrete form to abstract or difficult models	C–F	Learn science (learn the major models)
II	You let students 'play' (in structured assignments) with a model, in order to gain more insight into it	C–F	Learn science (learn the major models)
III	You have students to make knowledge and application assignments with regard to a specific model	C–F	Learn science (learn the major models)
IV	You discuss the function and characteristics of models in science	B	Learn about science (learn the nature of models)
V	You discuss the similarities and differences between a model and its phenomenon	B	Learn about science (learn the nature of models)
VI	You discuss the historical development of a specific model	B	Learn about science (learn the nature of models)
VII	You have students to observe phenomena and test the usefulness of a specific model to explain their observations	A	Learn to do science (learn to produce and revise models)
VIII	You have students to determine and debate on which points a certain model works better (making the understanding or predicting of a phenomenon better) than another model	A	Learn to do science (learn to produce and revise models)
IX	You have students to make predictions based upon a model and test them	A	Learn to do science (learn to produce and revise models)
X	You have students to make a scale model and compare it with the original object	A	Learn to do science (learn to produce and revise models)
XI	You have students to create a simple model	A	Learn to do science (learn to produce and revise models)
XII	You have students to discuss their models	A	Learn to do science (learn to produce and revise models)

models and modeling in PUSc were supplied as elements to be compared (see Table 11.2). So as to be recognized by the teachers, these activities were taken, almost literally, from the ANtWoord method. The activities corresponded to our interpretation of the three aims of PUSc, that is, to learn the major models (Domains C to F), learn about the nature of models (Domain B), and learn to produce and revise models (Domain A). A number of construct dichotomies, or bipolar constructs (see Table 11.3), were developed by the authors, based on statements selected from an earlier interview with each teacher, conducted by the first author (cf. Henze, van Driel, & Verloop, 2007).

Table 11.3 Rep grid constructs (perceptions of educational activities)

	Left pole of the construct	Right pole of the construct	Category of the construct
A	This activity is *time consuming*	This activity is *not time consuming*	Activity
B	Here by students mainly develop *scientific knowledge*	Here by students mainly develop *research skills*	Activity
C	This is an activity *typical for PUSc*	This activity belongs more to the *traditional science subjects*	Activity
D	For this activity *little pre-knowledge* is required	For this activity a *lot of pre-knowledge* is necessary	Activity
E	This activity is more suitable for *16-year-old students*	This activity is more suitable for *older students*	Student
F	With this activity, students are *actively working*	With this activity, students tend to be *passive*	Activity
G	For this activity *I have sufficient knowledge*	For this activity *my knowledge is not sufficient*	Teacher
H	This activity is more attractive to *science students*	This activity particularly attracts *non-science students*	Student
I	This is one of *my favorite* activities in the PUSc syllabus	*I don't look forward* to this activity	Teacher
J	This activity is rather *abstract*	This is a *concrete* activity	Activity
K	This is fairly much a *basic activity for me*	This activity *costs me a great deal of preparation*	Teacher
L	This is a *motivating activity for students*	This activity is not *motivating for students*	Student
M	This is more *suitable for pre-university students*	This is more *suitable for general students*	Student
N	This activity *works well*	*I don't have a good grasp* of this activity	Teacher
O	This activity is *teacher centered*	This activity is *student centered*	Activity

Constructs to be scored according to (1) agree with left pole; (2) partly agree with left pole; (3) neutral; (4) partly agree with right pole; (5) agree with right pole

To chart the development of science teachers' personal knowledge about teaching models and modeling, the designed rep grid instrument was applied twice: first in April 2002 and second in May 2004. Between these two moments in time, no interventions were conducted. The teachers were asked to rate 12 educational activities in terms of 15 bipolar constructs which should be regarded as representing extremes in a five-point scale or construct dimension running left to right from a value of 1 to a value of 5. By rating, teachers were able to indicate the comparative degree to which elements fit comfortably at or between the construct poles in relation to the other elements (Pope & Denicolo, 1993). The rating of the elements took place individually, at a location chosen by the teachers. This was usually their classroom or a small office at the school. The whole process, including instruction by the first author and the completion of the grid by the participant, took about 45 min.

The Semi-structured Interview

In addition, with all teachers a semi-structured interview on their PCK of models and modeling was held in the Spring of 2002, 2003, and 2004. The interview questions were developed on the basis of the results of a study of the relevant literature on PCK, on the one hand, and models and modeling in science education, on the other hand (Table 11.4). To make this subject concrete (to the teachers), a series of questions was asked on Chapter 3 of the ANtWoord workbook, titled 'Solar System and Universe' (Domain F). In this chapter, students have to develop models to describe and explain the earth's seasons and discuss them in the classroom afterward. Students also learn different models of the solar system, such as Ptolemy's geocentric model and Copernicus' heliocentric model, and debate their strengths and weaknesses. In the context of this chapter, the teachers were questioned about four distinct knowledge elements of PCK (Grossman, 1990; Magnusson, Krajcik, & Borko, 1999, p. 99), namely, knowledge about (1) instructional strategies concerning a specific topic, (2) students' understanding of this topic, (3) ways to assess students' understanding of this topic, and (4) goals and objectives for teaching this topic in the curriculum. All interviews took place privately in a place chosen by the teacher, shortly after he had finished the chapter on the Solar System and the Universe. The interviews took 1–1.5 h. Afterward, all interviews were transcribed in full.

Table 11.4 Some general phrasings of interview questions on the teachers' PCK

PCK elements	Questions on the teachers' PCK
(1) Knowledge about instructional strategies	1. In what activities, and in what sequence, did your students participate in the context of this chapter? Please, explain your answer 2. What was (were) your role(s) as a teacher, in the context of this chapter? Explain your answer
(2) Knowledge about students' understanding	3. Did your students need any specific previous knowledge in the context of this chapter? Explain your answer 4. What was successful for your students? Explain your answer 5. What difficulties did you see? Explain your answer
(3) Knowledge about ways to assess students	6. On what, and how, did you assess your students in the context of this chapter? Explain your answer 7. Did your students reach the learning goals with regard to this chapter? How do you know? Explain your answer
(4) Knowledge about goals and objectives of the topic in the curriculum	8. What was (were) your main objective(s) in teaching the topic of 'Models of the Solar System?' Explain your answer

Data Analyses

In this section, we discuss how the research data from the rep grid method (research question 1) and the interviews (research question 2) were analyzed.

Rep Grid Data Analyses: Research Question 1

As the elements were rated according to the constructs, it was possible to apply statistical methods of analysis to the teachers' raw grids. To analyze the rep grid data, we used the computer program Rep IV (Research Version 1.00; Gaines & Shaw, 2004). Rep IV is a set of tools for analyzing and comparing rep grids and producing graphic representations or plots of construct networks. In this chapter, we confined ourselves to a description of the method and results of the data analyses with FOCUS and COMPARE.

FOCUS Sorting and Hierarchical Clustering

The FOCUS program reorders the information in the raw grid by placing closely matching elements (elements that are rated similarly) together and also placing closely matching constructs (constructs that are used in the same way) together. The major criterion for forming groups or clusters is that the linear reordering of the rows of constructs and the columns of elements, respectively, will result in a final grid that displays a minimum total difference between all adjacent pairs of rows and columns (Shaw, 1980). The patterns resulting from the similarities that one attributes to both constructs and elements reflect coherent domains of meanings that are used to explain certain issues (e.g., knowledge about specific educational activities on models and modeling in PUSc) at a particular point in time (Bezzi, 1996). Repeated rep grid administration and analysis may indicate the changes over time in these personal meanings. The first and second grids (completed in 2002 and 2004) of the nine teachers in the study were subjected to FOCUS cluster analysis. Next, each analyzed grid was examined with respect to the way FOCUS grouped the elements (i.e., educational activities on models and modeling corresponding to the Domains A, B, and C–F), and grouped the constructs (i.e., the teachers' perspectives on these activities).

COMPARE

The COMPARE program evaluates the ratings in two different grids and shows the absolute differences between these ratings. We used this program to compare each teacher's second grid (2004) with his first one (2002). We examined the plots produced by comparing the grids, thoroughly, defining those constructs and elements which ratings had changed most over time.

The outcomes obtained with FOCUS and COMPARE resulted, for every individual teacher, in a description of how elements and constructs were related (representing the teachers' knowledge of educational activities) in 2002 and 2004, and the most important changes in these relationships (representing the teachers' knowledge development) between 2002 and 2004. In a following step, we compared these outcomes for all nine teachers in the sample, looking for parallels in their knowledge (development).

Interview Data Analyses: Research Question 2

The analysis of the interview data in 2002, 2003, and 2004 was related to the content and development of the teachers' PCK development. To analyze the teachers' responses to the interview questions, the authors developed codes for the four distinct knowledge elements of PCK (Table 11.4), as defined by Grossman (1990) and Magnusson et al. (1999). The final codebook was the result of different steps of testing and adapting the codes, until the authors reached consensus to all codes to be used.

Knowledge About Instructional Strategies (1) and About Students' Understanding (2)

Similar codes could be employed for knowledge about instructional strategies concerning the topic of 'Models of the Solar System and the Universe' and knowledge about students' understanding of this topic (PCK elements 1 and 2; Table 11.4). To describe these knowledge elements, three codes were developed from the PUSc curriculum: (i) a code representing the content of models (teachers have knowledge about the teaching of specific concepts in relation to certain models and have knowledge about students' understanding of these concepts); (ii) a code standing for the thinking about the nature of models (teachers know how to make students reflect on the nature of models and have knowledge about their students' understanding of the nature of models); (iii) a code related to the production of models, that is, teachers know how to stimulate students' model production (i.e., students' thinking up and construction of physical models) and model testing and have specific knowledge about students' modeling skills (e.g., students' creativity and coming up with new possibilities, which is an important step in the modeling process). These three codes can be linked, roughly, to the PUSc Domains, C–F, B, and A, respectively.

Knowledge About Ways to Asses Students' Understanding (3)

After reading the teachers' responses to the interview questions about ways of assessment in the context of teaching 'Models of the Solar System and the Universe', it was found that the teachers' knowledge about ways to assess students' understanding (PCK element 3) of this topic could be described using the following codes referring to different ways of assessment: (i) written test on model content; (ii) oral or poster presentation, or account, as products of students' self-directed work; (iii) paper or essay on the students' reflection upon the nature of models; (iv) students' modeling activities; (v) classroom debate on the geocentric and heliocentric models; (vi) portfolio on the preparation of the debate on models; and (vii) observation of group-work.

Knowledge About Goals and Objectives of the Topic in the Curriculum (4)

Regarding the knowledge about goals and objectives for teaching ‘Models of the Solar System and the Universe’ in the PUSc curriculum (PCK element 4), it was decided to describe the teachers’ responses on the relevant interview questions using two different kinds of codes. First, generally speaking the teachers expressed their epistemological perspectives. In analyzing these perspectives, Nott and Wellington’s (1993) classification of epistemological views was applied, on the basis of which three codes were developed: (i) positivist, in which models are seen as simplified copies of reality (e.g., Teacher 1: ‘Students have to understand that models are reductions of reality and not the truth’); (ii) relativist, in which models are seen as one way to view reality (e.g., Teacher 3: ‘It should not be taken for granted that a phenomenon can be modeled in one way; you can look to things from different perspectives’); and (iii) instrumentalist, in which the question is whether models ‘work’ instead of ‘being true’ (e.g., Teacher 5: ‘I have my students to understand that a model has not to be real and true to be useful’). Second, teachers’ statements about using models in the classroom were coded in terms of the various functions of models in science (Giere, 1991): (i) to visualize and describe phenomena; (ii) to explain phenomena; (iii) to obtain information about phenomena that cannot be derived directly; (iv) to derive hypotheses that may be tested; and (v) to make predictions about reality.

After coding the teachers’ statements on the interview questions, we put together for each teacher, the applied codes per PCK element in 2002, 2003, and 2004. Then, we identified for each teacher the combination of codes that arose across the different elements, per year. To chart possible common patterns in the knowledge (development) of different teachers, we compared these combinations across all nine teachers and across the years of data collecting.

Results from the Data Analyses

In this section, we will briefly discuss the results from the data analyses in order to answer the two research questions (see Section Method and Procedure).

Research Question 1: Rep Grid Results

Comparing the analyzed rep grids of the nine teachers in 2002, it became apparent that activities from Domain A (learn to produce a revise models) are not grouped together with activities from Domain B (learn the nature of models). As a group or a cluster of educational activities can be understood as representing a combination of activities that is rated similarly on the constructs, this means that in all the grids a distinction is made between the perception of certain educational activities from Domain A and certain activities from Domain B of the PUSc curriculum.

Domain A activities, for example, 'You have students to create a simple model' (XI) and 'You have students to discuss their models' (XII) (Table 11.2) have been scored, very similarly, as being activities which are 'active' (F) and 'concrete' (J). (Activity Constructs, Table 11.3). Whereas Domain B activities, such as 'You discuss the functions and characteristics of models in science' (IV) and 'You discuss the similarities and differences between a model and its phenomenon' (V), have been scored by the teachers as 'passive' and 'abstract' on the same constructs. In addition, Domain A activities were generally scored as being 'motivating for students' (L) and 'suitable for younger students' (E), whereas Domain B activities were rated 'not motivating' and more 'suitable for older students.' (Student Constructs, Table 11.3). On the other hand, activities from Domain A and activities from Domain B have been scored very differently on teacher constructs (Table 11.3), for example, 'I have (not) sufficient knowledge for this activity'(G) and 'This is fairly much a basic activity for me' versus 'This activity cost me a great deal of preparation' (K).

In all grids, different activities from the Domains C–F (learn the major models) are grouped together with certain activities from Domain A (learn to produce and revise models) or with activities from Domain B (learn the nature of models). This means that these activities have been perceived either in the same way as activities from Domain A or as activities from Domain B.

As we found that the teachers' perceptions of the educational activities differed mainly on teacher constructs, we decided to use these constructs, in an attempt to typify the personal knowledge of the nine teachers. First, we investigated which combinations of activities, in each grid, were more or less similarly rated as 'favorite activity' (I), 'sufficient knowledge for this activity' (G), 'basic activity' (K), and 'activity that works well' (N) (teacher constructs, Table 11.3). In a following step, we compared the combination of activities we found in each grid, across the nine grids (2002), and, as a result, three types of combinations were identified. These were interpreted as three types of teachers' personal knowledge about educational activities concerning models and modeling in public understanding of science (cf. Henze et al., 2007) (see Table 11.5)

Comparing the results from the data analyses of the nine teachers with these three types, we considered the content of the personal knowledge of two teachers more or less indicative of Type 1, the knowledge of three teachers indicative of Type 2, while the personal knowledge of four teachers could be qualified as representative of Type 3, in 2002.

With regard to the development of the teachers' personal knowledge, we inspected and compared each teacher's knowledge change between 2002 and 2004, based upon their most changed elements and constructs (data analyses with COMPARE). First, we explored whether patterns could be found in the combinations of elements from the various PUSc domains, and constructs (i.e., Teacher, Student, and Activity), which had changed most significantly or most often. This exploration, however, did not reveal specific patterns, indicating a certain type of change. At a more general level of speaking, the change of the teachers' personal knowledge about educational activities on models and modeling can be

Table 11.5 Types of teachers' personal knowledge about educational activities on models and modeling

Type 1	The learning of specific subject matter (Domains C–F) is connected with a discussion of the similarities and differences between models and phenomena and a discussion of the functions and characteristics of scientific models in general (Domain B). These educational activities are perceived as abstract, developing scientific knowledge, and more suitable for older students (Grades 11, 12) and pre-university students
Type 2	Students' observation of phenomena and students' production and discussion of simple (scale) models (Domain A) are combined with letting students play with physical models to enhance their understanding of specific subject matter (Domains C–F). These educational activities are perceived as active, concrete, aimed at developing skills, and more suitable and motivating for younger students (Grade 10)
Type 3	Students' reflection on the nature of models in science (Domain B) is combined with the learning of specific subject matter (Domains C–F). Educational activities used in teaching are perceived as abstract, suitable for older students (Grades 11, 12) and pre-university students, and attractive to students following the 'science and technology' stream in upper secondary education
	Students' model testing and revision (Domain A) is combined with the learning of specific subject matter (Domains C–F). These educational activities are perceived as activities for which a certain amount of pre-knowledge is required and as more suitable for older students (Grades 11, 12)
	Students' production and discussion of simple (scale) models (Domain A) is combined with the learning of specific subject matter (Domains C–F). These activities are considered to be suitable for younger students (Grade 10) and particular attractive to students following the 'humankind and society' educational stream

characterized by either an expansion or an endorsement of initial ideas and perceptions. For example, educational activities from the different PUSc domains were increasingly (i.e., more often and stronger) perceived to be passive or active, motivating or not motivating. Moreover, based on the observation that particular educational activities were increasingly appraised as 'working well' and 'basic,' it may be hypothesized that the teachers' ideas about these educational activities were manifested more clearly in their teaching practice over time.

Research Question 2: Interview Results

As a result of the analysis of the interview data from the year 2002, we were able to construct two types of teachers' PCK of 'Models of the Solar System and the Universe': Type I and Type II (Table 11.6). Type I of PCK is mainly focused on the transmission of the content of certain models of the Solar System, whereas Type II of PCK is associated with students' construction of knowledge and skills with regard to model content, model creation or comparison (e.g., debating), and reflection on the nature of models in general. (cf. Henze, van Driel, & Verloop, 2008).

Table 11.6 PCK Types I and II

PCK elements	PCK Type I	PCK Type II
Knowledge about instructional strategies	Knowledge about specific multimedia (film, video) and concrete materials to support students' understanding of model content and knowledge of ways to connect models with reality	Knowledge of motivating and challenging assignments to promote students' learning of model content; Knowledge about effective ways/methods to promote students' thinking about the nature of models (e.g., debating, modeling activities); Knowledge about ways to stimulate students' creativity
Knowledge about students' understanding	Knowledge about students' understanding (e.g., knowledge about students' abilities to think three dimensionally or to connect models with reality) is not very specific	Knowledge of students' motivation to discover things (model content) themselves; Knowledge of students' motivation and abilities to participate in modeling and related thinking activities (modeling skills); Knowledge of student's affinity with specific models (understanding of the nature of models)
Knowledge about ways to assess students	Knowledge about examinations of model content and application using written exams, oral presentations, posters, and reports	Knowledge of how to evaluate model content, model production, and thinking about the nature of models using exams, oral presentations, reports, portfolios, and (group) observations
Knowledge about goals and objectives of the topic in the curriculum	Epistemological views which can be understood as positivist and instrumentalist. Knowledge about the use of models to visualize and explain phenomena	Epistemological views: instrumentalist and relativist; Knowledge about the use of models to visualize and explain phenomena, to formulate and test hypotheses, and to obtain information about phenomena

Type I of PCK: Focused on Model Content

In Type I, knowledge about instructional strategies (PCK element 1) includes knowledge of a variety of concrete examples and visual tools to explain Copernicus' heliocentric model to students (Grade 10) in front of the classroom. Students' building of the heliocentric model with sticks and balls and a lamp were aimed at connecting their observations of phenomena (positions of the sun, the moon, and stars) with this model. Students' designing of their own models based on observations was seen as too difficult for students and of no sense. Some attention must be paid to other models of the solar system (ideas of Pythagoras, Aristotle, and

Ptolemy) and to the key roles played by Tycho Brahe, Johannes Kepler, and Galileo Galilei in getting the heliocentric model accepted in preference to the geocentric model, by astronomers. A classroom debate on the geocentric and heliocentric models, however, was seen as a waste of time because of students' lack of knowledge and understanding and the level of abstract reasoning required. Knowledge about students' understanding (element 2) includes knowledge about students' (in)abilities to think three-dimensionally, to connect models with reality, and/or students' difficulties with the scientific contingency of models, that is, the hypothetical character, and the ways in which models gradually develop (e.g., students' complaining about 'learning something that will change, anyway'). Knowledge about ways to assess students' understanding (3) includes knowledge of examinations, (oral) presentations, and reports, to assess both students' content knowledge of models and their use of models as 'tools'(e.g., to explain the seasons, to explain eclipses of the sun and the moon). Knowledge about goals and objectives in the curriculum with regard to models and modeling (4) reflects a combination of positivist and instrumentalist views. Models (i.e., models of the Solar System and the Universe) are seen as reductions of reality, aimed at visualizing and explaining different phenomena (cf. van Driel & Verloop, 1999).

Type II of PCK: Focused on Model Content, Model Creation, and Model Thinking

In Type II, knowledge about instructional strategies (PCK element 1) includes knowledge about motivating and challenging tasks that are aimed at supporting students' (Grade 10) understanding of model content, model production, and the nature of models. For instance, students' observations of time with help of a sundial are used to explain the time and direction of sunrise. To promote their understanding of (and creativity in) model production, the students are pushed to design different models (e.g., to explain the moon phases) from the same set of data. In addition, students' reflection on the history of models of the Solar System and the Universe is meant to support their thinking about the nature of models. Knowledge about students' understanding (element 2) includes knowledge about students' motivation, specific difficulties and inabilities concerning the content of scientific models and modeling activities, and knowledge about students' affinity with specific models (e.g., students' sympathy for geocentric models of the solar system, in which the earth or the sun is moving up and down to explain the seasons). Knowledge about ways to assess students' understanding (3) includes knowledge of examinations, students' presentations, reports, observations of modeling and debating activities (e.g., in classroom debates or in settings with university professors, invited over to the school), and logs and portfolios to assess students' learning and thinking processes. In the knowledge about goals and objectives for teaching models and modeling in the curriculum (4), not only the visualization and explanation of phenomena are emphasized, but also how to formulate and test hypotheses, and how to obtain information about phenomena. Models are conceived of not only as instruments but also as ways to view reality, implying that models are of limited use and are adaptable (i.e., a relativist epistemological view; cf. van Driel & Verloop, 1999).

We compared the answers and reactions of the nine teachers with the characteristics of Type I and Type II, and as a result we considered the PCK of five teachers to be more or less indicative of Type I, while the PCK of the other four teachers was classified as representative of Type II.

PCK Development

Comparison of the interview data from the years 2002, 2003, and 2004 revealed the following with respect to the development of the teachers' PCK. First, the results indicated that, in developing their PCK, all teachers extended their initial knowledge, over time. In addition, the ways in which the two types of PCK developed over the years appeared to be qualitatively different in terms of relations between the four PCK elements.

With regard to Type I, we found that in particular the knowledge about instructional strategies further developed. The results indicate that this development was mainly influenced by the teachers' interpretation of students' results on assessments. With regard to the development of PCK elements in Type II over the years, we found that changes in the knowledge about instructional strategies, the knowledge about students' understanding, and the knowledge about assessment were mutually related. In both types of PCK, the initial knowledge about goals and objectives of the learning and teaching of 'Models of the Solar System and the Universe' did not change heavily (cf. Henze et al., 2008).

Conclusions

To answer the general research question ('How can the content and the development of experienced science teachers' knowledge of learning and teaching models and modeling be typified in the first few years of teaching a new syllabus on PUSc?'), we summarized the results on the two specific questions, per teacher, in a table (Table 11.7).

We then analyzed the results so as to find any relationships between the teachers' personal knowledge about educational activities on models and modeling and their PCK of Models of the Solar System and the Universe. We compared the relationships found across the nine teachers, defining two different types of knowledge about the learning and teaching of models and modeling in public understanding of science (PUSc), Type A and Type B. Type A can be described as more oriented toward the learning and teaching of 'science as a body of knowledge,' whereas Type B can be typified as more oriented toward 'the experience of science as a method of generating and validating such knowledge' (Hodson, 1992, p. 545).

Table 11.7 Overview of the results

	Personal knowledge about educational activities			PCK of models of the solar system		Knowledge about learning and teaching models and modeling	
Teacher	Type 1	Type 2	Type 3	Type I	Type II	Type A	Type B
T1	x			x		x	
T2		x		x		x	
T3			x		x		x
T4		x		x		x	
T5			x		x		x
T6			x		x		x
T7	x			x		x	
T8		x		x		x	
T9			x		x		x

Type A: Science as a Body of Knowledge

In Type A, knowledge about learning and teaching models and modeling in Grade 10 is focused on the transmission of subject matter (Domains C–F in the PUSc curriculum). Knowledge is aimed to help students understand the major models. To this end, a variety of concrete materials and visual tools must be applied. For students to gain more insight, it is useful that they work with physical models and connect these models with (own) observations of real-life phenomena. To get a clear understanding, some knowledge about a model's history of development is also considered valuable. With older students and pre-university students, similarities and difficulties between a model and its phenomenon can be discussed, as the main functions of scientific models which are to visualize and to provide (causal) explanations for phenomena. Knowledge about effective instructional strategies developed in the time of the study. In addition, educational activities concerned with models and modeling in PUSc are increasingly perceived as 'working well' and 'basic.' We considered the knowledge of five teachers to be indicative of this type of knowledge (T1, T2, T4, T7, and T8) (see Table 11.7).

Type B: Science as a Method of Generating and Validating Knowledge

In Type B, knowledge about learning and teaching models and modeling in Grade 10 is focused on students' making of concrete (scale) models, as well as students' creation and revision of simple models based on (own) observations to facilitate their comprehension of the content and nature of specific models. In this light, a classroom debate on historical models and on students' own models is seen as helpful, too. Moreover, these debating activities are meant to promote students' understanding of the nature of scientific models, in general. Although aforementioned activities can be done by Grade 10 students (especially by pre-university students and those students from the 'science and technology' streams), just like activities to make predictions and to test hypotheses based on models, these activities are perceived as more suitable for older students (Grades 11, 12). In 2002, the knowledge of effective instructional strategies about models and modeling was already perceived as sufficient, and most of the educational activities were more or less recognized as 'basic' and 'working well.' Changes, over time, in the knowledge about instructional strategies, the knowledge about students' understanding, and the knowledge about ways to assess students, were closely related. The knowledge of four teachers was qualified to be indicative of knowledge Type B (T3, T5, T6, and T9) (see Table 11.7).

Discussion and Implications

Both the analysis of the rep grid data (research question 1) and the analysis of the interview data (research question 2) were based on the three aims of PUSc (Table 11.1) which correspond to the Domains C–F (learn the major models), Domain A (learn to produce and revise models), and Domain B (learn the nature of models). Because of this, we were able to connect the results of the analyses and to construct a more general characterization of the teachers' knowledge about learning and teaching models and modeling in PUSc (cf. Kagan, 1990).

The outcomes of the study show that the content of knowledge Type A is more limited with regard to knowledge about instructional strategies, students' understanding, and ways of assessment than knowledge Type B. In addition, in Type A, it was mainly the knowledge of instructional strategies that developed further, over the period of the study. In Type B, on the other hand, the development, over time, concerned the different knowledge elements, which appeared to be related. Furthermore, the content and development of Type A includes knowledge about the functions and characteristics of models in science, in which models are seen as instruments and reductions of reality, mainly aimed to describe and explain phenomena (instrumental and positivist epistemological view). In Type B, however, models are seen as instruments and as just one way to view reality, which functions are not only to visualize and explain phenomena, but also to formulate and test hypotheses and obtain information about phenomena which cannot be derived directly (instrumental and relativist epistemological view).

Possible Explanations of the Differences Between Type A and Type B

There is some indication in the study that differences in (the development of) the teachers' knowledge about learning and teaching models and modeling in PUSc are related to differences in their students' backgrounds and ages. That is, it is apparent that teachers who represent knowledge Type A taught the PUSc syllabus to students in Grade 10, while teachers representing Type B taught various parts of the new syllabus to older students (Grade 11). Moreover, three out of four teachers representing Type B taught a course entitled ‘PUSc-plus’ (about the nature of science) to students in Grade 12, in addition to teaching the regular PUSc syllabus to students of Grades 10 and 11. As the development of teachers’ knowledge is often seen as rooted in classroom practice (Shulman, 1986), in a process mentioned in literature as ‘tinkering’ (Wallace, 2003) and ‘bricolage’ (Hubermann, 1993), the differences between the content and development of knowledge Type A and Type B may be explained by differences in the teachers’ classroom experiences, related to differences in their students’ backgrounds and ages.

It can also be argued that differences between knowledge Types A and B can be explained by differences in the teachers’ understanding of the history and philosophy of science (cf. Gallagher, 1991) and/or knowledge and skills with regard to model production and model revision (cf. Crawford & Cullin, 2002), at the start of the introduction of PUSc (in 1999). As teachers’ knowledge and beliefs largely influence their teaching practice (Pajares, 1992), these differences may have led to different choices with regard to instructional strategies and/or teaching specific types and ages of students, which may have led, consequently, to differences in the content and further development of teacher knowledge Types A and B.

Implications

One of the main aims of the new syllabus on PUSc is to improve students’ understanding of the nature and characteristics of science. In this light, we proposed that the learning of scientific models (PUSc curriculum Domains C–F) and the act of modeling, that is, the production and revision of models (Domain A), should go hand in hand with the development of the capacity to make informed judgments on the role and nature of models in science (Domain B). In order to achieve these aims, it is necessary for teachers to have an adequate understanding of the purposes of using models and modeling in science (education). On the basis of the results of this study, we concluded that those teachers who are representing Type B of teacher knowledge about teaching models and modeling in PUSc have more extended knowledge and may have realized more aims of the new syllabus than those teachers representing Type A. To expand the teachers’ knowledge, professional training could be designed, for instance, to develop the teachers’ knowledge about the history and philosophy of science (Domain B) and their skills in producing and revising models (Domain A). In addition, the teachers (especially those teachers representing Type A) could increase their teaching experiences (i.e., teaching more classes and students of different ages, educational levels, and streams). From a more general constructivist view on the development of professional knowledge, and the idea of teachers being ‘reflective practitioners’ (Calderhead & Gates, 1993; Fullan & Hargreaves, 1992; Schön, 1983), it is deemed important that teachers are provided with opportunities and facilities to reflect on teaching experiences in order to articulate and share their personal knowledge and beliefs. We think that explicating personal professional knowledge and sharing it with colleagues or student–teachers could be the main key to effective (further) professional development of (experienced) science teachers (cf. Wallace & Louden, 1992).

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Chapter 12
Teaching Pre-service Elementary Teachers to Teach Science with Computer Models

Nicos Valanides and Charoula Angeli

Introduction

Science education encompasses different roles, including the learning of science, learning about science, and learning how to do science. More specifically, science education targets to help learners to construct scientific conceptual knowledge, understand issues in the philosophy, history and methodology of science, and become able to take part in activities aiming at the refinement of the existing or the acquisition of new scientific knowledge (Hodson, 1992). Models are also integral to thinking and working in science and constitute "science's products, methods, and its major learning and teaching tools" (Gilbert, 1993, p. 10).

Hestenes (1996) stressed that science content includes, in most cases, abstract concepts and/or phenomena, which are often inaccessible. These abstract entities require an external representation in concrete and analogical forms, so they become comprehensible to learners. Models are representations that can be conceptual, visual, interactive, or mathematical, which are used to represent science content in concrete and simplified forms to facilitate learner understanding. These external representations tend to "make familiar the unfamiliar" (Nagel, 1961), while students' intuitive models "can serve as a central guidepost for sustaining very open, student-directed inquiry investigations" (Clement, 2000, p. 1044). Mental models constitute mental entities that are personal and internal representations of any target system that is being modeled and are used to reason with them. The external representations of the target that are generated or manifested through different material descriptions, such as action, speech, or written language, constitute the expressed models (Gobert & Buckley, 2000). Models are constructed when an object or a phenomenon is too small, too large, too complex, or too distant, in both time and space, or when the object or phenomenon is otherwise inaccessible. They constitute important tools that enable scientists to generate predictions, as well as guide explanations, interpretation, understanding, and discovery in science (Jungck & Calley, 1985). Modeling

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7_12,

tools provide scientists with new ways for creating theories, testing ideas, and analyzing data. Scientists make observations, identify patterns in data, and then develop and test explanations of these data using scientific models. Certain aspects of the nature of science that are directly related to the use of models are tentativeness and the need for continual revision and evaluation. Models and modeling activities in science should include and cultivate the tentativeness of models, the role that creativity plays in building models, the iterative aspect of modeling, and the fact that scientists can have more than one model representing the same phenomenon or object.

Model-based teaching constitutes a process of constructing mental models of phenomena by coordinating resources of information, learning activities, and instructional strategies, so that mental model building both in individuals and in groups of learners is optimally fostered. Constructing mental models through instruction can turn out to be a process of conceptual change associated with the corresponding difficulties. In most cases, learners' pre-existing intuitive models encompass their preconceptions and natural reasoning skills present before instruction (Clement, 2000) that cannot be observed directly. Thus, learning approaches that can challenge students' conceptual ecology and take them from preconceptions to accepted consensus models following in most cases different learning pathways (Niedderer & Goldberg, 1995), or a sequence of intermediate steps, should be carefully designed and implemented. Hestenes (1996) stated that there are many reasons for using models in science teaching, such as (1) model construction provides an interactive environment for student engagement leading to significant learning gains; (2) working with models can enhance system-thinking abilities; (3) model development is useful for helping students to develop skills in graphing and mathematical computation and visualization; and (4) models can enable students to run experiments or simulations using different assumptions without any harmful consequences.

Computer modeling can also make scientific material more accessible and interesting. For example, computer microworlds offer students access to worlds that cannot directly experience and create a sense of owning and directing the dynamics of these worlds (diSessa, 1985; Papert, 1980). Computer models can also facilitate the processing of complex data, make the scientific process more dynamic, and provide ways for studying interesting and complex phenomena. Additionally, many computer-modeling tools, such as MARS, Model-It, STELLA, and ThinkerTools (Metcalf, Krajcik, & Soloway, 2000; Raghavan & Glaser, 1995; Raghavan, Sartoris, & Glaser, 1998; Stratford, 1997; White, 1993), when appropriately used, can promote subject matter understanding, inquiry skills, and systems thinking (Richmond, 2001).

Undoubtedly, pre-service and in-service teachers should develop an understanding of the nature of science, including the knowledge that scientists formulate, and test explanations of the nature of science using, among other things, theoretical and mathematical models. De Jong and Van Driel (2001) stated that pre-service teachers lack knowledge about the use of models in science and that there is a pressing need to engage all prospective teachers in rich modeling activities so that they become able to use models in science teaching and learning. Smit and

Finegold (1995) reported that prospective science teachers had a view of scientific models as merely a representation used by someone who understands a phenomenon to explain it to someone who does not. Van Driel and Verloop (1999) also reported that even experienced science teachers failed to acknowledge how models are used in making predictions, or how models are used as tools for obtaining information about a target that is inaccessible for direct information. Students' involvement in the process of creating, testing, revising, and using scientific models can help them make their thinking visible and test aspects of their conceptual frameworks. Student inquiries should culminate in formulating an explanation or constructing a model. In the process of answering questions, students should engage in discussions and argumentation that can possibly result in revision of their explanations (National Research Council, 1996). For these reasons, the National Science Education Standards (National Research Council, 1996) require science teachers to be knowledgeable in many aspects of scientific inquiry and the nature of science, including the role of models and modeling. The standards also call for science educators to focus on model-centered instruction by integrating appropriate technology in science teaching for the purpose of engaging students in inquiry and in a process of constructing knowledge (American Association for the Advancement of Science, 1993a, 1993b; Gilbert, 1993; Hestenes, 1996; Jungck & Calley, 1985; National Research Council, 1996). This of course presupposes that teachers, either in-service or pre-service, are systematically involved in creating, expressing, testing, and continually revising models so they become competent to teach science with models. Unfortunately, the role of models and modeling in science is usually a neglected aspect of scientific inquiry and the nature of science. Thus, teachers' preparation in science often focuses primarily on the acquisition of facts and information and conveys an image of scientific inquiry that is not aligned with the real nature of science or the scientific practice (Anderson & Mitchener, 1994). Many teachers also view models as representations of real-world objects or events and not as representations of ideas about real-world objects or events. Furthermore, they do not possess adequate knowledge and skills related to building models for supporting students in learning science, learning about science, and learning how to do science (Justi & Gilbert, 2002). Besides, many science textbooks, including those that present scientific models, fail to identify them as such, and what are usually termed "science process skills" are experienced through "cookbook" or verification-type laboratory activities (Harrison, 2001).

From this perspective, teachers' pre-service preparation and in-service professional development should involve inquiry learning and experiential learning as advocated by reforms in science education (Loucks-Horsley, Hewson, Love, & Stiles, 1998). Penner (2000/2001) argues that one method that could possibly assist the inquiry learning process is computer modeling. Modeling usually involves investigating real-world phenomena, as well as designing, building, and testing computer models related to a real-world investigation. Such modeling tools differ on a variety of dimensions, including the extent to which they focus on problem solving or theory development, and whether they engage students in exploring pre-made models or designing their own models.

Despite the ongoing interest in models and modeling in science teaching and learning, there is only limited information regarding in-service and pre-service teachers' knowledge about models and modeling in science. Furthermore, only few studies attempted to measure and/or describe changes resulting from some form of intervention. De Jong and Van Driel (2001) investigated the development of prospective science teachers' content knowledge and pedagogical content knowledge in the domain of models and modeling in the context of a postgraduate teacher education program. Surprisingly, their findings indicated that these prospective science teachers, who held Masters of Science degrees in chemistry, did not have pronounced knowledge about models and modeling, and that some of the important functions of models, such as making and testing predictions, were rarely mentioned by them. Crawford and Cullin (2004) also investigated the influence of instruction on prospective secondary science teachers' understandings about modeling in the context of a model-based instructional module. They reported that prospective teachers became more articulated with the language of modeling, but they did not exhibit full understanding of scientific modeling.

Thus, teacher educators should carefully consider the use of models in teacher preparation and integrate into their instructional practices lessons for preparing science teachers to teach with models. The authors of this chapter have joined the efforts of other teacher educators (i.e., Crawford & Cullin, 2004; De Jong & Van Driel, 2001; Smit & Finegold, 1995; Van Driel & Verloop, 1999) in conducting systematic research for the purpose of developing instructional models to guide teacher training in the pedagogical uses of computer models in science teaching (Valanides & Angeli, 2006, 2008). Valanides and Angeli (2006, 2008) discuss the design and effects of two relatively short instructional interventions of about 2.5 h each on pre-service teachers' skills to design science lessons with models. In their research, Valanides and Angeli (2008) engaged teachers in both expressive and exploratory modeling activities. In explorative modeling, learners were asked to explore ready-made models that represented somebody else's conceptions, try out a model, look at cause and effect relationships, and draw conclusions based on the results of their exploration. In expressive modeling, learners expressed their own ideas and developed a model or an external representation of their ideas. Subsequently, they used their models to test hypotheses and, based on the results of their investigations, they revised their models for the purpose of improving them. In examining the quality of teachers' science lessons, the criteria focused on whether (a) pre-service teachers' models had a correct structure, (b) pre-service teachers' models were real or naïve, and (c) pre-service teachers integrated in their science lessons explorative and/or expressive modeling experiences (Bliss, 1994). In addition, Valanides and Angeli (2008) reported that despite the fact that 90% of the participants had no previous experience with modeling in science, after the intervention teachers developed a more articulate way to talk about models within the context of computer modeling. The results of this research are encouraging, but it was evident that student teachers needed more time with either learning how to use computer-modeling software or the process of learning how to construct a model. The authors hypothesized that it may be the case that with more time and engagement in rich modeling activities more students at the end will be able to construct viable scientific models and become competent in teaching science through models. These results were in agreement with the results of other studies, which also engaged prospective teachers in the act of model building (Crawford & Cullin, 2004; De Jong & Van Driel, 2001). The findings also suggested that further research efforts were needed to explore effective ways of how to gradually support teachers in achieving higher levels of expertise in constructing scientific models, understanding their significance, and integrating them effectively in real classroom practices. The observed difficulties that prospective teachers face provide the impetus for continuing research efforts in teaching teachers how to teach science with models and the results are promising and indicate that prospective teachers can benefit from these learning experiences in terms of both understanding science concepts better and developing pedagogical skills about how to teach science through models. The results also point out that teacher educators should undertake serious and coordinated efforts in systematically integrating computer-modeling tools in science education courses.

Therefore, the purpose of this chapter is to present an improved instructional design model that was developed and tested in a design-based experiment during the fall semester of 2009 and then discuss its effects on pre-service elementary teachers' skills to design science lessons with computer models.

Methods

Participants

Sixty-two first-year pre-service elementary teachers who were enrolled in an instructional technology course participated in the study. Students were required to participate in 13 whole-class (lecture) meetings and in thirteen 75-min computer lab sessions (about 20 students in each lab). Prior to taking the instructional technology course, students completed a basic computing course where they learned how to use general-purpose software. Participants did not have any previous experience with neither Model-It, the software that was used in the study, nor constructing conceptual or computer models in order to teach science topics. The majority of them were also not familiar with model-based teaching and were thus not informed or knowledgeable about the use of models in teaching and learning.

The Computer-Modeling Tool

Model-It, the computer-modeling tool that was used in the study for constructing computer models, is a learner centered and an easy to use tool for constructing and testing dynamic, qualitative models (Jackson, Stratford, Krajcik, & Soloway, 1994; Metcalf et al., 2000; Stratford, Krajcik, & Soloway, 1998). The model construction process scaffolded by the software includes three stages. First, the learner creates the

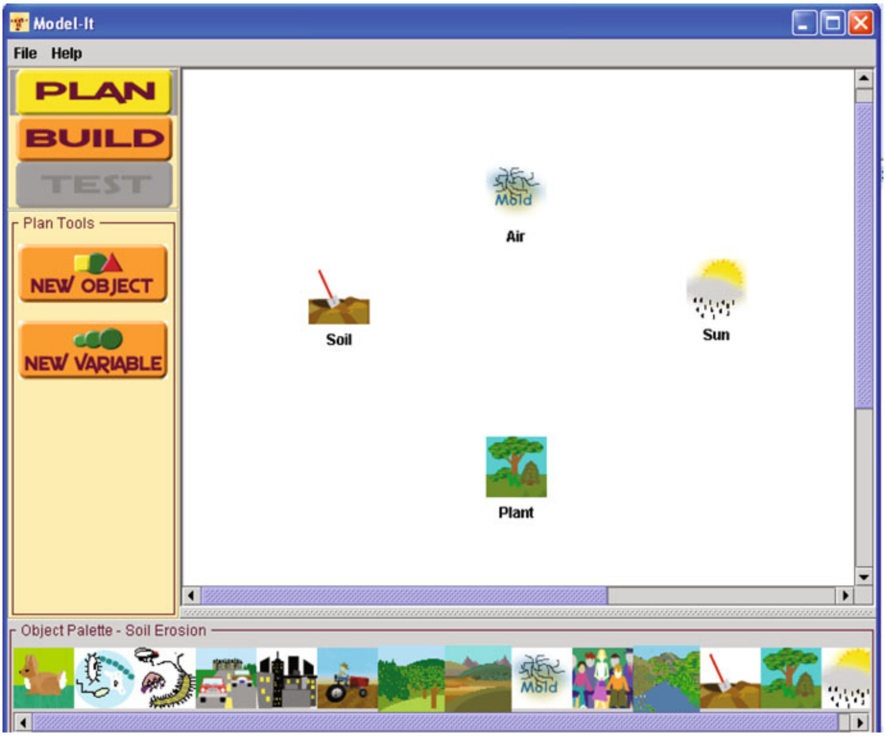

Fig. 12.1 Identification of entities

entities of the system. For example, in Fig. 12.1, the entities of the system include the sun, plant, soil, and air. The software allows the user to associate an icon with each entity.

Second, the user creates the variables for each entity. Variables are defined as the measurable characteristics of an entity, such as shown in Fig. 12.2, light is a variable relating to the sun, water is a variable relating to the humidity of the soil, growth is a variable of the plant, and carbon dioxide is a variable relating to the atmospheric air as mixture of gases.

Third, variables are designated as causal or affected depending upon the direction of the relationship between them. As shown in Figs. 12.3 and 12.4, Model-It supports a qualitative, verbal representation of relationships (Jackson et al., 1994). Relationships are defined in terms of two orientations (i.e., increases or decreases) and different variations (i.e., about the same, a lot, a little, more and more, less and less).

After the development of a model, the user can test it. Figure 12.5 shows the meter, which displays a variable's current value at run time. Only the values of independent variables can be adjusted while the model is running. There is also another tool called the simulation graph, which presents a line graph displaying how factors change over a series of time steps.

Obviously, the learners, when using the software, draw upon their own understanding of phenomena to define objects, identify variables, and create relationships.

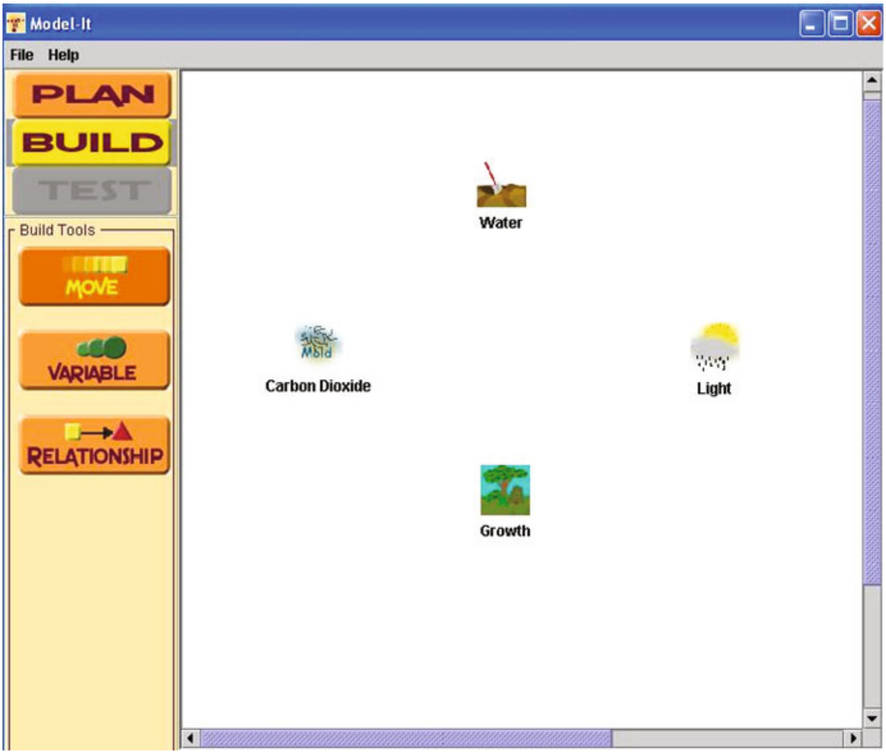

Fig. 12.2 Definition of variables for each entity

Then, they test their models and based on the interpretation of the outcomes, they revise them. While Model-It supports students in model construction by providing appropriate computer scaffolds for each one of the development phases, it cannot provide students with feedback regarding the correctness of their models. Therefore, students need to realize that they can use the software to develop an external representation (i.e., a model) of their internal representation and, based on the quality or precision of the simulated outcomes of the model, to revise the model appropriately. Obviously, an expressed model at a specific time represents students' current understanding. The simulated outcomes obtained from running the model can trigger thinking for criticism and improvement leading to cycles of revision. This process is extremely important for conceptual change and growth.

The Instructional Design Model

A 5-h intervention was designed and implemented for training pre-service teachers how to teach with computer models. The 5-h intervention was divided into four sessions of 75 min each. The instructional sequence of the intervention is shown in Fig. 12.6.

The instructional intervention was situated in students' teaching experiences. In other words, the intervention was not conducted in a context-free fashion where

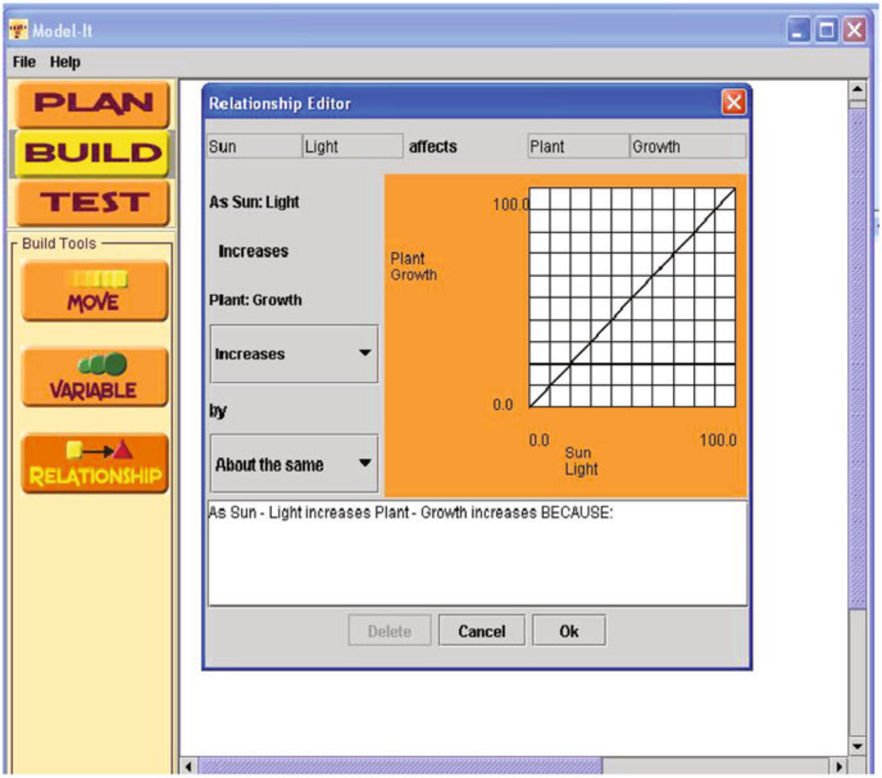

Fig. 12.3 Definition of relationships in Model-It

traditional practices usually involve lectures about the new topic and practice examples (Brown, Collins, & Duguid, 1989; Greeno, 1997; Putnam & Borko, 1997, 2000). The approach was gradually developed by the authors in a number of design-based research studies (Design-Based Research Collective, 2003) and endured several cycles of modifications. It departs from traditional systems-oriented approaches to instructional design and moves toward a more systemic and authentic design process where context-specific factors, i.e., affordances of technology, content, pedagogical strategies, setting, and learners, are considered in increasing detail throughout the design and development process. The departure from traditional instructional design models was deemed necessary, because teachers' instructional design decisions are usually guided by a body of knowledge that is highly situated within the context of classrooms and teaching (Carter, 1990; Kagan & Tippins, 1992; Leinhardt, 1988; Moallem, 1998).

As shown in Fig. 12.6, pre-service teachers were first asked to study the science curriculum and select a topic they considered difficult to be taught and understood by learners. In the case of in-service teachers, teacher educators can ask them to reflect on their classroom experiences and based on them to propose a topic. Then,

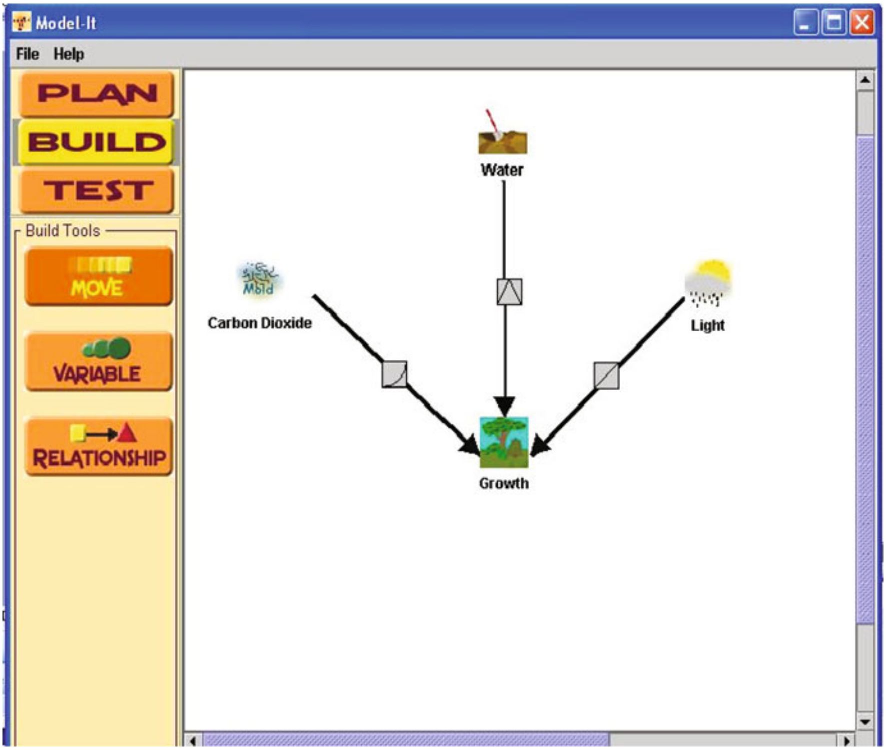

Fig. 12.4 Establishment of relationships between the variables

pre-service teachers were asked to indicate why they felt the topic they proposed was difficult and to analyze the underlying content in terms of the scientific concepts and/or principles that it entailed. Subsequently, they were asked to transform the content using appropriate representations, so that it could be better understood. Models were introduced as a form of representation. In order for students to better understand models and modeling, the researchers asked them to think about a well-known phenomenon experienced by all of them, namely, the growth of plants. Students were asked to depict the phenomenon using a diagram. In doing so, students were gradually discovering the basic elements that needed to be taken into consideration in order to create the representation. For example, students were saying that a plant needs light, water, carbon dioxide, and soil to grow. The researchers then introduced students to systems terminology and explained that a model consists of entities, variables, and relationships. A revised model was then created by the students that showed in more detail and in a systematic way the structure of the model in terms of its elements (i.e., entities, variables, relationships). Thereafter, students learned how to use Model-It in order to build and test the model they constructed regarding the growth of plants.

The instructors explained to the students that Model-It was powerful enough to assist the model-building process through its scaffolds (i.e., Plan, Build, and Test)

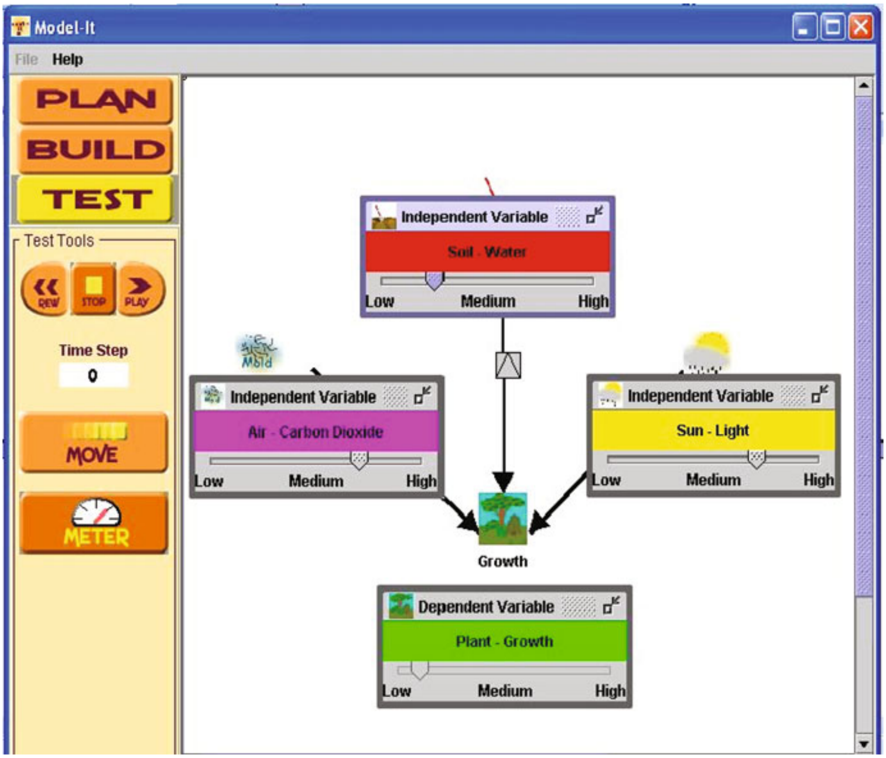

Fig. 12.5 Testing of a model in Model-It

and that they could think of the model-building process as consisting of three stages, namely create entities, define variables, and build relationships among variables. The model that students constructed consisted of four entities, namely plant, the sun, soil, and air. Then for each entity, they defined variables, such as growth for the plant, light for the sun, water and nutrients for the soil, and carbon dioxide for the air. Subsequently, students were asked to think about any cause and effect relationships among the various variables.

Initially, students suggested using only linear relationships for all variables to indicate that an increase in the value of the causal (independent) variable will affect the dependent variable by about the same amount. For example, as the amount of water in the soil increases, the growth of the plant will also increase by about the same amount. Similarly, as the amount of light (i.e., duration of the day) increases, the growth of the plant will also continue to increase, irrespective of the amount of water or carbon dioxide, etc. It was interesting, however, to observe that gradually students changed their minds and experimented with relationships of different variations (i.e., about the same, a lot, a little, more and more, less and less, bell-shaped curve) once they found out about them.

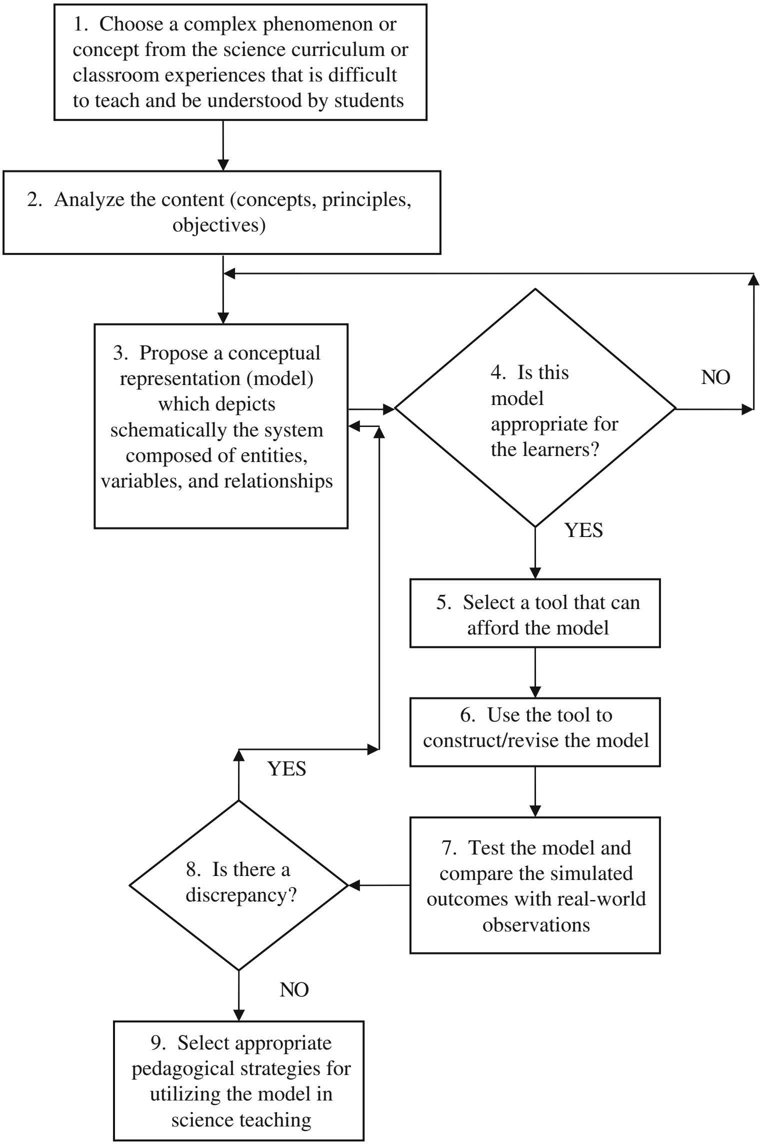

Fig. 12.6 Instructional design model

Then, the researchers asked students to run the model and control variables in order to test their initial hypotheses. Students did not really know how to control variables to test their hypotheses, so extra instructional time was devoted for teaching students how to control variables. Also, students showed a weakness in understanding the difference between independent and dependent variables. This became evident when they ran the model and were wondering why they could not change the values of all variables. The researchers then devoted class time in explaining the differences between the two types of variables. When students ran the model and observed the simulated outcomes, they started suggesting revisions of the model.

Thus, it progressively became evident to them that their current knowledge about the phenomenon was apparently not enough and that they needed more information about it before changing the model. The researchers asked the students to think about the model at home and to present in class the revised model during the next meeting. In the next session, students presented and defended their new models or revised models in class. Then, the researchers spent time in discussing with students the pedagogical uses of models in teaching and learning. Students were concerned that model building appears to be a difficult cognitive activity for elementary school children and indicated that they were willing to use them in sixth grade only. Even with sixth-grade students, student-teachers felt that model construction would be difficult and suggested that teachers first provide students with ready-made models to explore (explorative modeling) and then gradually, as students become more familiar and comfortable with systems, teachers can move to expressive modeling where students are asked to develop their own models from scratch.

Assessment Task

The researchers asked the pre-service teachers to design a sixth-grade science lesson of about 80 min (two teaching periods of 40 min each) in which computer models and Model-It could be integrated for the purpose of meeting learning objectives. A design template was given to the students to scaffold for them the pedagogical integration of Model-It in teaching and learning. Succinctly, the template included nine items that could be regarded as instructional design decisions that students needed to make. First, students needed to select an appropriate topic that could be better taught with models than traditional instructional strategies (i.e., demonstration, lecture.). Second, they needed to define learning objectives for the content to be taught. Third, they needed to design an instructional design sequence to be carried out in the classroom with their students, which included the following seven instructional events: (a) orient the student, (b) diagnose initial conceptions, (c) create cognitive conflict, (d) construct new understandings, (e) apply new knowledge, (f) compare new with old conceptions, and (g) defend the added value of the computer tool in the lesson designed.

Each one of the nine instructional elements was explained in the classroom and the researchers used different examples to illustrate each one of them. Students were assessed on each one of the nine items individually and a total grade for all nine elements was also calculated. The highest assessment score possible was 55. Analytically, the maximum score for item one was 5 points, for item two 5 points, item three 5 points, item four 5 points, item five 5 points, item six 10 points, item seven 5 points, item eight 5 points, and item nine 10 points. Students' lessons were also analyzed qualitatively to answer questions regarding the structure of the models, the complexity of the models, and the integration strategies that students suggested for utilizing the models in the classroom.

Results and Discussion

Table 12.1 shows descriptive statistics regarding students' performance on each one of the design elements as well as their total design score.

Table 12.1 Descriptive statistics of learners' performance on the design task ($N = 62$)

	Range of scores	*M*	SD
Selection of appropriate topic	0–5	3.26	0.77
Specification of objectives	0–5	4.02	0.88
Student orientation	0–5	3.58	0.97
Diagnosis of initial conceptions	0–5	3.79	0.87
Creation of cognitive conflict	0–5	3.71	0.98
Construction of knowledge	0–10	6.60	1.19
Application of new knowledge	0–5	3.52	1.18
Comparison of new with old conceptions	0–5	3.98	1.23
Software added value	0–10	6.60	1.19
Total score	0–55	39.09	6.09

As shown in Table 12.1, students' performance was well above the average for each one of the nine items indicating that despite students' lack of prior instructional design knowledge they benefited from the 5-h intervention and were able to complete the design task satisfactorily. The average performance shows that students needed more training in the constructivist uses of computer models during learning. This finding was also evident from the qualitative analysis of students' lesson plans.

The qualitative analysis showed that topics of interest to teach with models included recycling, electricity, the digestive system, photosynthesis, electromagnetism, circulatory system, friction, types of soil and their characteristics, and respiration of plants. In general, students selected appropriate topics to be taught with models, but it was also pointed out to them that some topics, such as electricity and magnets, could be better taught with hands on activities at least at first and then to gradually move to the use of computer models. In addition, the data show that all pre-service teachers used the explorative method where they prepared a model for their students to explore and draw conclusions based on the simulated outcomes of the model. Student-teachers recognized the fact that their integration strategies could have be more constructivist; however, they explained that they chose to use the explorative method, as opposed to the expressive method, because they considered model development from scratch to be a cognitive task with a significant amount of difficulty for sixth graders. However, they indicated that model creation and integration in science teaching ought to probably be viewed from a developmental perspective meaning that teachers first introduce their students to ready-made models for the purpose of teaching them about systems terminology and structure, then teachers provide their students with semi-completed models that students are required to complete by themselves, and finally students are asked to create their own models.

Interestingly, unlike the findings in our previous research (Valanides & Angeli, 2006, 2008), where student-teachers did not understand the use of models as cognitive tools that can be used to represent an internal model and thereafter use this external representation to test hypotheses and theories, 78% of the student-teachers in this study showed with the instructional activities that they proposed that they had a good understanding of the instructional value of models. For example, it was evident from the lesson plans that student-teachers engaged students in activities where they needed to form a theory about the issue at hand or explain a phenomenon by running the model and testing various hypotheses.

Also, in contrast with the results of our previous research (Valanides & Angeli, 2006, 2008), student-teachers' models were not "naïve" or safe. For example, in Valanides and Angeli (2008), we reported that 87% of student-teachers constructed models which had two or three entities, one variable per entity, and linear relationships of the form "as *X* increases *Y* increases by about the same amount." These models were over-simplistic and probably indicated that participants held naïve beliefs or naive internal mental models about science content and naïve beliefs about the epistemological aspects of scientific modeling. Moreover, it was also stated that student-teachers could be classified as Level II modelers according to the classification scheme of Grosslight, Unger, Jay, and Smith (1991). According to this classification scheme, level II modelers realize the purpose of a model, that is, they view models as related to ideas and that there is not a one-to-one correspondence with reality or do not consider models "as little copies of real-world objects" (Grosslight et al., 1991, p. 819). Consequently, level II modelers' viewpoints go beyond a simple copy theory epistemology, and they do realize that some aspects of a model may be wrong and need to be changed. What level II modelers do not realize is that a model is a tool to trigger thinking in a community of learners and not a representation of some phenomenon that is used by an expert to explain a complex phenomenon to a novice.

In the present study, student-teachers showed that they cared to develop a good understanding of the underlying science content to be taught before attempting to create a model for it. Therefore, 76% of them developed models with at least three entities and three variables per entity. As a result, the models student-teachers developed in this study were far more sophisticated and advanced than the models student-teachers developed in our previous studies, indicating that student-teachers in the present study were above level II, but we do not have enough data to conclude that student-teachers in this study approached level III.

Concluding Remarks

The instructional design model that was employed in the study to teach student-teachers how to teach science with models proved to be effective and feasible to be implemented in a 5-h instructional program. Initially, pre-service elementary teachers were almost completely ignorant about the role of models and modeling in science teaching and learning, indicating that through most of their secondary education and probably college education, students were never asked or encouraged to think with models (Valanides & Angeli, 2008). After the intervention, the majority of the students were, however, able to use the scaffolds of Model-It and build models that were conceptually correct. There was also evidence that the student-teachers developed a more articulated way of thinking and talking about the role of models in science teaching and learning and gradually developed a deeper conceptual understanding as they were trying to make sense of the validity of the simulated outcomes. They also refined or improved their qualitative understanding relating to several science processes, such as predictions, control of variables, or the coordination of theory with evidence.

The extent to which models are used in science and their potential impact on learning and understanding science coupled with recent technological advancements that brought computer modeling into the realm of everyday activities provide a challenge for further investigating their potential impact on learning and understanding science. It is our strong belief that if teacher educators undertake coordinated efforts in systematically integrating computer-modeling tools in science courses, then prospective teachers will understand science content and teaching better. Obviously, understanding models and modeling helps students to understand the nature of scientific knowledge as a human construct and that models may differ in their ability to approximate, explain, and predict real-world phenomena.

The findings suggest that it is necessary to engage prospective teachers in extensive rich modeling experiences throughout their coursework in order to help them understand that scientific models are not mere representations, but actual tools for thinking and learning that play an essential role in scientific inquiry. Teacher educators are thus faced with the additional challenge to cultivate the belief that model-based teaching and learning are important for teachers' pedagogical content knowledge that encompasses "the ways of representing and formulating the subject that make it comprehensible to others" (Shulman, 1986, p. 9). These limitations coupled with the absence of any "coherent knowledge that underlines the cognitive processes involved in model-based learning" or "any coherent theories of how model-based teaching should be approached" (Gobert & Buckley, 2000, p. 891) are not aligned with the recognized importance of models in science teaching and learning and provide a challenge for further investigating models' potential impact on learning and understanding science.

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M.S. Khine, I.M. Saleh (eds.), *Models and Modeling*, Models and Modeling in Science Education 6, DOI 10.1007/978-94-007-0449-7,

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