Is There a Connection? The Role of Meta-Modeling Knowledge in Learning with Models

Christina V. Schwarz

332 Erickson Hall, Michigan State University, East Lansing, MI 48824

Tel: (517) 432-4851, Fax: (517) 432-5092

Email: cschwarz@msu.edu

Abstract

Scientific models (including computer simulation models) are increasingly and successfully being used in science instruction. Indeed, if one thinks of models as any set of rules, representations, or reasoning structures that can predict and explain, then model-creation, testing, revision, and use lie at the core of science and should play a significant role in science education. Recently, researchers have begun to consider how knowledge about the nature of models and the process of modeling (or meta-modeling knowledge) may play an important role in how students and teachers learn with models. Preliminary experimental evidence indicates that a better understanding of the nature of models may help students better interpret scientific information from models and make better inferences from their own models. This paper draws on several research studies about epistemic knowledge to begin sketching a causal theory for (1) why a connection between meta-modeling knowledge and learning with models may exist, (2) what the causal components of this connection may be, (3) whether there are reasonable alternative explanations that may account for the relationship between meta-modeling knowledge and scientific understanding, and (4) why it is important to explicitly address epistemic forms and games in learning environments. This paper concludes with implications of this work for science instruction and with directions for future research.

Introduction

If one defines a scientific model as any set of rules, representations, or reasoning structures that allows someone to generate predictions and explanations, then creating, evaluating, revising and using models can arguably be considered to lie at the core of the scientific endeavor. For this and other reasons, many have advocated the use of models in science education (Gilbert & Boulter,2000; Gilbert & Ireton, 2003; Halloun & Hestenes, 1987; Lehrer & Schauble, 2000; Mellar, Bliss, Boohan, Ogborn, & Tompsett, 1994; Papert, 1980; Resnick, 1999; Spitulnik, Krajcik, & Soloway, 1999; White & Frederiksen, 1998). In addition, there is strong evidence that various types of models used in conjunction with strong curricula and instruction can foster model-based reasoning, conceptual change, systems-thinking, and a number of other important aspects of learning (Mandinach & Cline, 1993; Raghavan & Glaser, 1995; Resnick, 1999; Richards, Barowy, & Levin, 1992; Schwarz & White, 2004; Spitulnik et al., 1999; White & Frederiksen, 1998).

Regardless of their potential merit, models and modeling are frequently used as instructional tools or processes in science education. Yet there is evidence to suggest that most students and teachers do not understand the nature of models or the process of modeling in which they are engaged (Grosslight, Unger, Jay & Smith, 1991; van Driel & Verloop, 1999, Schwarz, 1998). Further, there is increasing evidence indicating that understanding the nature of models and the process of modeling may improve learning with models. In other words, understanding the epistemic forms of science may be important in understanding the products of science (such as models), and in generating the products of science (Gobert & Discenna, 1997; Grosslight, et al., 1991; Hammer, 1994; Schwarz & White, 2001; Smith, Maclin, Houghton & Hennessey, 2000; Songer & Linn, 1991).

Before continuing, let me define a few terms. I use the word meta-modeling knowledge to include people's understanding of the nature, utility, and evaluation of models, their understanding of the process of modeling, and how this understanding is used in their reasoning with models. (As an aside, it is important to note that although meta-modeling knowledge is different from metacognition or the awareness and regulation of cognition, reflection may provide a critical mechanism that produces awareness or understanding for both metacognition and meta-modeling knowledge.) Other terms used in the literature that connote similar or related ideas include 'epistemologies of models,' (a subset of epistemological beliefs or stances) 'meta-conceptual modeling knowledge,' and even sometimes 'meta-representational competence.' More broadly, I am referring to knowledge of epistemic forms and games (Morrison & Collins, 1995) or an understanding of "target structures that humans use to construct knowledge, and …the strategies, moves, and constraints associated with these forms." In this sense, various models act as epistemic forms and types of modeling as epistemic games (e.g. system-dynamic models, aggregate-behavior models, situation-action models are all types of process-analysis games) (Collins & Ferguson, 1993). There are many other useful forms and games in which one can be engaged in science (e.g. structural-analysis games, functional analysis games, and perhaps even more generic games such as experimentation and argumentation), though I have chosen to focus on models and modeling as they provide a particularly fruitful lens with which to help students understand the nature of science when defined broadly and used as an analogical tool (Schwarz, 1998).

To further clarify the definition of models used in this text, models can range in form from a physical scale model of the solar system, to computer simulations that predict how galaxies can collide, to explanatory laws such as "when no forces are acting, an object's velocity remains the same because there is nothing causing it to change."

Returning to the original argument, some researchers have found an empirical relationship between an understanding of the nature of models and students' subject matter expertise (Gobert & Discenna, 1997; Schwarz & White, 2001). Similarly, others have found relationships between students' understanding of the nature of science or learning with their subject-matter performances (Hammer, 1994; Songer & Linn, 1991). Overall, however, the science education community knows little about *how* understanding more about models (or more broadly, meta-representational expertise and epistemic knowledge) affects learning science content from models and reasoning with models.

Given that this may be an important aspect of science education, it is the aim of this paper to use evidence and theory from a range of cognitive psychology literature to (1) present evidence of a potential relationship between meta-modeling knowledge and an understanding of science, (2) provide causal explanations for the connection between them as provided by these research studies, (3) present alternative explanations that account for the evidence of this connection, and (4) present an argument for why epistemological forms and games should be explicitly addressed in science instruction. The overarching goal of this work is to better understand the role of meta-modeling knowledge in science learning, in order to advance theory on the relationship between meta-representational expertise and learning/performance, and to use these findings to inform curriculum design and instruction.

Empirical Evidence and Causal Explanations for a Relationship Between Meta-modeling Knowledge and Scientific Understanding

In the recent past, several researchers have designed empirical studies to determine the relationship between meta-modeling knowledge and scientific understanding (Gobert & Discenna, 1997; Schwarz, 1998; Smith, Snir, & Raz, 2002). While it has been considerably difficult to disentangle meta-modeling knowledge from content knowledge expertise, initial trends suggest a possible link between articulated understanding of models and scientific understanding. For example, Schwarz found that after an intervention enabling middle school students' to understand the nature of models and the process of modeling, that students' general understanding of models was correlated with their understanding of physics content knowledge as determined by written pre/post tests (Schwarz, 1998; Schwarz & White, 2004). In a similar study, data correlating students' epistemological perspectives on knowing and learning physics (VASS survey) were correlated with physics performance (Halloun & Hestenes, 1998 as reported by Leach, 2002). However, neither of these studies provided causal evidence for the relationships between epistemic or meta-modeling knowledge and scientific understanding.

Nonetheless, these results are intriguing. Suppose that further studies support these findings. Does that mean that meta-modeling knowledge and other forms of meta-representational expertise are worth teaching explicitly in order to improve content understanding? Before arriving to that conclusion, we need to further analyze whether the causal explanations for the relationship between meta-modeling knowledge (and more generally epistemic knowledge) and science understanding seem reasonable. The research below suggests there are reasonable explanations for why meta-modeling knowledge may be related to students' science performance. However, those explanations appear to be specific to the task and purpose of the educational context.

For example, in my prior work with pre-service elementary teachers (Schwarz, 2002), I found some evidence suggesting that the teachers who understood that models are not exact replicas of objects and phenomena (and therefore have strengths and limitations as representational devices), may understand which models (or parts of models) to use in their own model-based reasoning and when to use those models. For example, the distance scale is frequently inaccurate in canonical solar system models. As such, it is important to understand that a model is usually created for specific purposes (in this case, illustration of the order of the planets), that it is similar and different from the physical system or object in significant ways (the planet order might be the same, but the scale distance, scale size, and color are often not). Some of these teachers learned that it is important to be cautious about internalizing information from a model that may be inaccurate with respect to aspects such as the distance scale.

There is additional evidence that students creating models to explain scientific ideas to others may benefit from a richer understanding of the form and purpose of models. Gobert and Discenna’s (1997) study found that students with more sophisticated epistemologies about models were able to make better inferences from the models they generated (physical diagrams of volcanoes) in order to reason about other plate tectonics phenomena such as convection in the earth. Gobert (personal communication, May, 2002) theorizes that students with more sophisticated epistemologies may have known more about the form of the representation they were creating (for example, that models are used for explanations) and re-constructed or constructed new knowledge to better explain the underlying scientific ideas.

In a study by Smith et al. (2002), researchers found that when students understood that models can be useful as explanatory tools, they used models to explain evidence and data. Specifically, students who understood that a computer model representing a particulate model of matter could be useful in understanding why mass but not volume is conserved across various transformations, used this computer model in producing explanations of the phenomena. This study also indicated that knowing that models can be evaluated by how well they fit the patterns of evidence can help students understand which model is the best and most believable model.

It is also important to note that epistemology literature related to science education generates some other causal connections between epistemic views and science performance. For example, Songer & Linn (1991) found that students who came to believe that science was relevant to everyday problems sought to understand underlying scientific principles and apply them to new situations. Hammer (1994) also found, among other aspects, that students who believed that scientific knowledge was coherent were more careful about building an integrated conceptual understanding.

What causal themes arise from this small sample of studies? It appears that understanding the nature of models, their forms, their purposes (including utility and applicability) and how to evaluate them may be critical in learning science with models. In other words, knowing the nature and form of the scientific product (the epistemic form/models) as well as how that product is generated (the epistemic game/some form of modeling) may help students better use and produce those products (play the game). However, this sample of studies also indicates that each educational context and purpose elicited different aspects of meta-modeling knowledge. For example, students may benefit from some dimensions of model understanding when they are given scientific models to learn from and use in their thinking. They may benefit from other dimensions when they are creating their own scientific models as explanations for others. Further, students may benefit from different dimensions of understanding models depending on whether the purpose for using the models is for gaining knowledge for future teaching, explaining the concepts to someone else, or personal understanding and sense-making. In retrospect, this context specificity of meta-modeling knowledge is sensible given that different scientific disciplines themselves use a variety of epistemic forms and games, and even these forms and games have changed over time.

These studies indicate that there are some reasonable, contextualized causal explanations for how meta-modeling knowledge (or epistemic knowledge overall) may affect students' or teachers' science learning. Are these causal explanations strong enough to explain correlations between meta-modeling knowledge or epistemologies and science performance?

Alternative Explanations For Correlation Between Meta-Modeling Knowledge and Performance

There are alternative explanations that may account for such results. For example, it is possible that learning science is, to some extent, an inherently epistemological activity (Leach, 2002). Connections between understanding the nature of models and student learning with models may be a result of the fact that understanding science entails an epistemic understanding for how to use scientific knowledge (models) in the world and what constitutes an adequate explanation (or model). Indeed, the work from Smith et al. (2002) indicates how closely linked scientific knowledge and meta-conceptual knowledge may be. Their study seems to indicate that content knowledge informs and is informed by meta-conceptual knowledge of modeling throughout the learning process.

It is even possible that students may not have generalizable understandings or beliefs for the nature of models, the nature of science, and so on, but an understanding of epistemic forms may be locally established to fit the circumstances and the learning environment (diSessa, Elby & Hammer, in press). DiSessa has referred to these types of understandings as local epistemological phenomenologies (diSessa, personal communication, July, 1996). On the other hand, some meta-conceptual or epistemological-like views may be more coherent and consequently more influential than others. The interesting research may involve determining which of these understandings and views may be most important or influential.

There have certainly been a variety of studies demonstrating students successfully engaging in modeling activities and in displaying representational competence without any particular evidence that metaconceptual knowledge of the activity has played a significant role. For example, Barowy & Roberts (2000) showed in their empirical work that students learned how to fruitfully engage in a science activity using a computer model to advance their theories without ever showing any marked improvement in their understanding of the nature of models. Of course, this could mean that the design of the assessment does not adequately measure or detect student's understanding, or it could mean that students' may not have generalizeable understandings of models. Additionally, Stevens & Hall (1998) found in two separate case studies that meta-representational expertise was either irrelevant to representation use, or very difficult to obtain. As Steven explains (personal communication, April 25, 2002) if one thinks of the representations as tools for doing work, "just like we would not expect a set of hand tools to [necessarily] provide meta-tool expertise," we might not expect people using representations to necessarily need meta-representational expertise. Nonetheless, Stevens notes that these results say nothing about whether such expertise is valuable or whether there is an overall difference in such competence between experts and novices.

Perhaps these studies lead one to think that what matters more than meta-modeling knowledge is meaningful modeling experiences that promote productive modeling practices. In other words, students may primarily need an experience base of summarizing patterns into models or using models to explain patterns in order to learn about models and benefit from knowledge of models. Lehrer & Schauble (2000) discuss the idea that being a good modeler may primarily entail having a number of good models to access which may require, "an extended participation in a context in which modeling has both a purpose and a payoff."

Alternatively, it may be that certain learning contexts scaffold or foster learner's epistemic knowledge so that learners no longer need epistemic knowledge to successfully engage in the learning activity. For example, in Barab, Hay, Barnett, & Squire's (2001) analysis of students' project-based work, students construct artifacts that serve as a medium through which they "engage in dialogues with peers, supporting the reflection and re-evaluation of their emerging understandings." As such, perhaps co-constructing projects gives rise to epistemic understanding without the need for explicit epistemic instruction.

Meta-Modeling Knowledge and Knowledge of Other Epistemic Forms and Games Should be Explicitly Addressed in Science Instruction

To summarize, it appears from the studies presented in this paper that meta-modeling knowledge and other epistemic knowledge related to learning may be at least partially contextualized (in that only certain kinds of meta-modeling knowledge may be relevant for learning in certain contexts) and may both improve and be improved by content knowledge itself as long as there is a base of experience to build upon. Additionally, this kind of knowledge is difficult to promote, may not be necessary for some kinds of learning, and may not be necessary in a learning context that already provides scaffolds for productive epistemic learning. The question then becomes, should we be addressing this type of knowledge in science instruction?

While the evidence of the impact of meta knowledge on other types of knowledge is not currently overwhelming, there are those including myself that argue that learning environments should nevertheless address meta modeling knowledge, and more generally, epistemic forms and purposes. I argue that if the primary purpose of science education is to help students become scientifically literate, then they must learn about the forms and the nature of the scientific endeavor. Therefore, epistemic forms and games should be an important component of the curriculum. As Morrison & Collins (1995) state, "An important function of schools is to help students become epistemically fluent or to be able to recognize and practice a culture's epistemic games.

Others apparently agree. For example, Driver, Leach, Millar, & Scott (1996) have suggested that model-based reasoning, a form of students' epistemological reasoning which entails their views of the form of scientific inquiry, the nature of explanation, and the relationship between explanation and description, is a critical component of science and an important objective of science education. Even if researchers do not explicitly discuss the value of recognizing a culture's epistemic games, others understand the importance practicing a culture's epistemic games. Lehrer and Schauble (2000) state that, "classroom learning of science and math should accurately reflect the essential nature of these disciplines as modeling practices. … [And that] modeling is the name of the game for significant portions of mathematical and scientific practice, so it is essential that the game not be postponed until high school."

Discussion and Implications for Science Education

This line of theory and research may provide some tentative implications for science education. (1) Science instruction should make use of epistemologically rich learning environments to help scaffold student epistemic knowledge even if epistemic knowledge is not explicitly addressed. Examples may include engaging students in creating models to explain or teach other students, or in collaborative work on projects whose final goal is producing an artifact or a better understanding of an idea. (2) Science instruction should use meaningful learning contexts for students so that models (or other epistemic forms) have both purpose and payoff. Within rich contexts, students may spontaneously generate understanding of epistemic forms and games. (3) Science instruction should explicitly address meta-modeling knowledge and other epistemic forms and games as a part of helping students understand the overall culture of science. It is important to make epistemic knowledge relevant to the science instruction, and to connect specific epistemic examples to more general epistemic understanding and instruction on the nature of science. (4) Finally, epistemic fluency may take a great deal of effort and may need to be addressed over a long period of time.

Future Directions in Research

The role of meta-modeling knowledge and epistemic forms in learning continues to be of interest to many, yet the field could benefit from additional research on how epistemic knowledge emerges and evolves in learning. As a symposium from AERA indicated (Schwarz, Gobert, Smith et al. 2002), at least four core issues about the topic remain. Those questions include: If epistemic knowledge exists, what form might it take? (Is it more context-specific or independent?) How can we assess it? (This depends on what form we believe this type of knowledge might take.) Is there evidence that fostering knowledge about epistemic forms and games is helpful to learning? If so, how can we develop instructional principles for fostering this type of knowledge? While not explicitly discussed in the symposium, another crucial issue is determining the role of epistemic knowledge and the effect of epistemic instruction on different learners.

This paper has partially addressed the first and third research questions with the expectation that the theory will be refined with further empirical evidence and additional insights from a broader range of literature such as that in the history, sociology, and anthropology of science. It is my aim to continue researching these questions by studying how meta-modeling knowledge emerges and evolves in model-centered learning environments.

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