A Simple Exercise Reveals the Way Students Think About Scientific Modeling

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Scientific modeling is an integral part of contemporary science, yet many students have little understanding of how models are developed, validated, and used to predict and explain phenomena. A simple modeling exercise led to significant gains in understanding key attributes of scientific modeling while revealing some stubborn misconceptions.

Scientific models are becoming increasingly important in the practice of contemporary science. Models permit scientists to elucidate the behavior of complex systems whose study would otherwise be problematic. Examples include the study of global warming, distant stars, pandemic epidemiology, natural disaster scenarios, nuclear development, atomic theory, and drug discovery. Many science education researchers consider modeling a critical component of scientific literacy for both scientists and the public (Gobart and Pallant 2004; White and Frederiksen 1998). An understanding of how models are created, judged, and validated is imperative if our political leaders, voters, and funding agencies are to make informed decisions about the future of this nation's natural resources and environmental health, and the physical and emotional health of its citizens. All of these areas are heavily dependent on the use of models to solve current problems and predict the behavior of systems well into the future. It is also critical for our science majors to be able to navigate the world of modeling if they are to be successful in a field that is increasingly model-dependent.

Despite the importance of scientific models to scientific discovery and advancement, students at the middle and high school levels often possess only superficial understandings of the nature of scientific models (Grosslight et al. 1991; Treagust, Chittleborough, and Mamiala 2002). One reason may be that although the American Association for the Advancement of Science (1993) and the National Research Council (1996) have designated the teaching of the nature of science and the scientific method as a priority, there is no emphasis placed on the nature of scientific models. Current college-level textbooks allocate few pages to the nature of science and even less to the underlying assumptions of scientific modeling.

The National Science Education Standards (NSES) stress the importance of students' competence in the following areas: ability to express a complex level of scientific knowledge, logical reasoning abilities, and analysis, in addition to being able to question others' results and accept judgment of their own ideas (NRC 1996). The NSES also emphasize the importance of student exercises that culminate in the formulation of their own theory or model to explain the phenomenon under investigation (NRC 1996). Simple exercises in scientific modeling have the ability to address all of these standards.

We contend that teaching about the *nature* of scientific models is as important as teaching the *results* of modeling exercises. Given the sophistication of scientific models, it is not surprising that many students face challenges in understanding the models. For science majors, understanding models is integral to their development as practicing scientists who will rely on the findings from scientific modeling to guide their own research. The teaching of scientific modeling is important, because this is often the only way to inform about an abstract scientific concept (Treagust, Chittleborough, and Mamiala 2002). When research is presented and shared among scientists, it is often a model that most clearly delineates the findings of the research. Through instruction in the nature of scientific modeling, we believe students will gain a greater understanding of the practice of science.

Theoretical basis for the intervention

Previous research on student understanding of scientific models

In what has come to be accepted as a seminal paper in the field, Grosslight et al. (1991) investigated student understanding of the nature of scientific models. Their study consisted of interviews of middle and high school students and a panel of experts in scientific modeling. To assess the subjects' depth of understanding, three levels of understanding associated with the nature of scientific modeling were developed.

Students who exhibited Level 1 understanding often considered models as miniature copies of reality and understood that data were used to create the model but not that data could be produced from the model. When students attained Level 2 understanding, they began to appreciate the purpose of the model. However, they did not show an understanding of a model's predictive ability and had a simple idea that new data may cause the model to change slightly. Level 2 students often understood parts of the model were missing but did not make any mention of why that may have been the case.

Level 3 understanding was characterized by the understanding that models possess explanatory and predictive power, undergo constant review and revision, and can be used as aids in the development of future experiments and theory. The experts interviewed agreed with the Level 3 characterization of the nature of scientific models. Grosslight et al. (1991) found the majority of students' understanding was consistent with Level 1. Extensive description of Levels 1 to 3 can be found in Table 1.

In more recent work, Crawford and Cullin (2004) designed a modeling experience for preservice teachers using a computer program called Model-It. The study found that preservice teachers made modest gains in understanding the nature of models and modeling by creating a dynamic model of an environmental system.

Constructivism

Scientists explore their environment, create meaning that is localized, and test that meaning against the observations reported by others. It is no wonder that there has been a push within the science education community to adopt a constructivist method of instruction in the science classroom for sometime (Chinn and Malhotra 2002; Etheredge and Rudnitsky 2003). In a constructivist environment, students are encouraged to question what they know and how they came to know what they know (Etheredge and Rudnitsky 2003). The constructivist classroom environment also enables students to approach problem solving and learning in a manner that reflects the methods by which a practicing research scientist would also approach learning (Ertmer and Newby 1993). Our modeling exercise encompasses a constructivist approach to learning.

Previous implementation of "black-box" interventions

There have been implementations of assorted forms of the black-box experiment with various age groups in an effort to increase student conceptual understanding of the nature of scientific models. Cartier (2000) developed a lesson on the nature of modeling using a black-box worksheet. She provided students with an explanation of the pattern of data that arose from a particular black box she had seen at a conference. Cartier encouraged students to better hypothesize what was in the box by brainstorming ideas and developing various representations of what they thought was inside the box. However, students did not actually experiment with the box themselves. Cartier followed the black-box experiment with a series of exercises on Mendel's simple dominance model, enabling students to apply their knowledge of the nature of scientific models to a specific content and understand the assumptions underpinning Mendel's model. Finally, students most often focused on trying to arrive at the right answer rather than becoming engaged in the process of developing acceptable scientific models (Cartier 2000).

Our working definition of a scientific model is that it should be explanatory and predictive, be consistent with prior knowledge, be dynamic, be assessed on a continual basis for reliability with current theory and experimental data, allow for the possibility of multiple acceptable models for the same phenomenon, and act as a guide to future research

(Cartier, Rudolph, and Stewart 2001; Barton 2001; Carey and Smith 1993; Grosslight et al. 1991).

Methods

The modeling experiment was conducted in a nonmajors introductory chemistry course (59 students), and an introductory course in chemical biology (14 students). The exercise took place during a regularly scheduled three-hour laboratory period. During the first two hours, small groups of up to four students were presented with a large black box (see opening photo). The box had an opening on top that was fitted with a funnel and plastic flexible tubing coming out of a hole on the bottom. Students were simply told to pour water into the box and observe what happened. Some of the boxes were preloaded with water (both clear and colored) in an effort to produce more complex data that differed from group to group. However, the pattern of data that emerged from the boxes was roughly the same. Through discussion within their group, students devised a paper-and-pencil model of the inner workings of the box. Students were shown two different methods for graphing the data, and were instructed to develop a representational model that could predict future data, explain current data, and explain any anomalies within the data set collected. At no time were students allowed to view the inside of the box.

The process of open peer review began during the third hour. Each group

TABLE 1

Grading rubric for qualities of models based on the assignments in Table 2.

Quality	Level 3 (Expert)	Level 2 (Informed novice)	Level 1 (Novice)	Pretest levels	Posttest levels
Models are explanatory and predictive	Models are used to explain patterns in phenomena, data, or observations.	Models are used to explain phenomena, data, or observations.	Models are used to explain.	1	2*
Role of theory and data in model making	Models are supported and created by the interplay of theory and data.	Models are created or supported by the use of theory and/or data.	Models are based on data alone.	1	3*
Predictive and explanatory nature of models	Models are used to predict and describe behavior of unknown systems.	Models can be used to predict or describe systems.	Models describe phenomena.	0	1*
Dynamic nature of models	Models can change with acquisition of new data or theoretical constructs.	Models can change with acquisition of new data.	Models can change.	0	0
Validation	Models are validated by scientists based on their ability to explain/predict data and overall utility.	Models are validated by scientists based on their ability to explain/predict data.	Models are reproduced by scientists.	1	2*
Model composition	Models can take different forms—physical, mathematical, or theoretical.	Models can be represented in physical form.	Models can be represented in different forms.	0	2*
Models themselves can guide research	Models play an integral role in guiding future research efforts into known and unknown systems.	Models play an integral role in guiding future research efforts into known systems.	Models can be involved in directing research.	0	0
Multiple models	There are multiple effective and legitimate models for most systems.	There can be more than one model for the same phenomena and they may both be acceptable.	There can be more than one model for the same phenomena.	0	0
Falsifiability	Models can be falsified by acquisition of new data, technology, and theory.	Models can be falsified by acquisition of new data.	Models can be falsified.	0	0

A level of 0 was assigned if the quality was not present in the concept map. *Wilcoxon signed-rank Z-score indicates statistical significance at the $p < 0.001$ level.

presented and defended their model during a student-generated question-and-answer session. The remaining class members had to critique, in writing, the strengths and weakness of each model presented and compare it to their own model. After all groups had presented their models, each group was given the opportunity to revise their model based on the information they had gained from their peers.

The pre- and posttest instrument was developed based on the theoretical framework that guides the black-box curriculum originally used in the MUSE project (2002). For our purposes, we used a set of open-ended written response questions (Table 2) and asked students to draw a hierarchical concept map that reflected their understanding of scientific models (Ruiz-Primo and Shavelson 1996). We then analyzed the data using the criteria set forth in Table 1, which corresponds to Grosslight et al.'s (1991) original work in the area. Each student response was assigned a level of expertise, in each area of interest, both pre- and postintervention. A Wilcoxon signed-rank Z score was then used to test for any difference in scores pre- and postintervention.

Results and discussion

We found a statistically significant but modest gain in the following attributes of scientific models: composition, explanatory and predictive nature, determination of limits and validity, and the various representations. However, the majority of students did not acknowledge the existence of multiple models, the dynamic nature of models, or the ability of models to be falsified. (See pre- and posttest responses below.)

Models are derived from a combination of theoretical constructs and data accumulation. At the start of the exercise, most students assumed that only data guided the construction of models, with the role of theory being largely ignored. By the end of the exercise, students were more aware of the complexity of model making and more likely to invoke both data and theory as integral to model making.

Pretest: "We create a model based on evidence and data."

Posttest: "… and sometimes scientists create models just from theoretical assumptions."

At the onset of the exercise, most students believed that models were little representations of reality and gave no regard to the explanatory and predictive nature of models. By the end of the exercise, most students understood the explanatory nature of models and began to release the notion that a model is simply a copy of reality. The exercise did not lend itself to the predictive nature of models, and hence no change in that area was noted.

Pretest: "Models are not an accurate representation of reality more so a representation of what one would consider to be a possible reality."

Posttest: "Models can explain why a process which includes behavioral systems takes place and infer upon this to predict future behavior." (Student goes on to give example from the model developed during this intervention.)

Many students assumed that models are validated by the process of replicating the work in question, believing that all work in science is reproduced prior to publication. After the exercise, students began to realize that much of science is not repeated but judged on standards of plausibility and the ability of the model to explain or predict phenomena. Students attributed the limitations of the model to a lack of data; no regard was given to scientist bias or theoretical development in the field. After the exercise, many students mentioned that they had not realized the power of peer review in validating models and uncovering biases and limitations.

Pretest: "Scientists repeat the experiment or think it is important."

Posttest: "Scientists compare the logicalness of the model with the evidence and by reviewing other models.They also critique each others work."

At the onset, most students could not give an example of a scientific model, and those who did used the model of the atom or the solar system as examples. When probed, most students felt that models were simply physical representations of phenomena. By the end of the exercise, students were able to give multiple examples of models having physical, mathematical, and theoretical forms, and many concluded that scientific modeling was complex and often contained elements of several different representations within the model.

Students did not show a conceptual gain in the area of the dynamic nature and falsifiability of models or the possibility of having multiple ac-

TABLE 2

Student assignments: Open-ended questions and concept mapping of models.

Open-ended questions

- How do scientists judge the importance of other scientists' work?
- What are the criteria for judging the validity or importance of any piece of scientific work?
- Describe scientific modeling.
- Respond to the following statement: Once a scientific model is created and accepted by the scientific community it does not change. There is a single, correct model for each phenomenon.
- Respond to the following statement: Models are an accurate representation of reality.
- What is the relationship among theory, experimental data, and scientific models?
- Describe any scientific model with which you are familiar.

Concept mapping

Use a concept map to show everything you know about scientific models. Include the following items: (1) how they are judged, (2) how they are created, (3) what they are used for, (4) what their purpose is, (5) their definition, (6) how they are communicated to other scientists, (7) types of models, and (8) any other information you think is applicable.

ceptable models for the same phenomena. Failure of student growth in the area of the dynamic nature of models is perplexing, because students actively changed their paper-and-pencil models while doing the black-box experiment and also changed their models in response to data acquired during the model presentation and peer-review process.

Students also did not change their conceptions about the ability to have multiple acceptable models. This was an unanticipated result, because 20 different models were presented for the same black box. Students were engaged in the process of critiquing other models and integrating the findings into their own systems. Also at the end of the session, students considered more than half of the models plausible, and most students were visibly frustrated by this turn of events. Indeed, months after the experience, students would still ask, "Which one was right?" Although they were looking for a "correct" model, they were unable to generate instances in which any model could be falsified—the hallmark of a scientific question.

It is suspected that students have been conditioned to expect a single correct answer to scientific inquiry, and that this level of change presents a serious challenge to their long-held thinking. We believe that the dynamic nature of models, the existence of multiple models, and falsifiability are all controlled by students' sense that there is always a right answer in science. Other researchers in the area (Harrison and Treagust 2000) have also noted resistance to change in these areas.

We feel that this exercise deepened understanding of scientific modeling for our students, which is crucial to understanding increasingly complex science content. Having gone through the entire process, students gained a perspective on scientific thinking and the generation of scientific findings that is likely unique given the peer review that was undertaken. Having this experience in hand, we think students will have a better appreciation for the authentic conduct of science, the generation and validation of scientific findings within the community, and the tentative nature of science. ■

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