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Transcending Simple Forms of School Science Investigation: The Impact of Preservice Instruction on Teachers' Understandings of Model-Based Inquiry

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This study examined 21 preservice secondary teachers as they engaged in activities aimed at fostering an understanding of the epistemic roles that models, theory, and argument play in scientific inquiry. Findings indicate that instruction can help preservice teachers develop more sophisticated understandings of scientific models and promote incorporation of model-based lessons in their classrooms. However, even with scaffolding, the majority of these preservice teachers were unable to use theoretical models to ground their own empirical investigations. Two factors shaped participants' thinking about these inquiries. One was previous school-related research experience, which influenced not only what they recognized as models but also the way they believed models could be incorporated into inquiry. The other was a widely held simplistic view of "the scientific method" that constrained the procedures and epistemic frameworks they used for investigations. On the basis of these findings, the authors offer a more focused, evidence-based design for instruction around model-based inquiry.

Keywords: epistemology, science inquiry, teacher learning

The primary professional task of aspiring science teachers is to translate their accumulated history of undergraduate and precollege learning experiences into engaging and appropriate instruction for young students. While this seems challenging enough, three factors converge that require this effort to be more a reinvention of understanding than mere translation of experience. First, the major science education reform documents encourage teachers to use problem solving and inquiry as the principal contexts for effective instruction, meaning that teachers should be able to mentor students through activities that emulate the disciplinary pursuits of scientists (see American Association for the Advancement of Science, 1993; National Research Council, 1996; National Science Teachers Association, 1995). Second, recent scholarship in science studies confirms that these disciplinary pursuits are methodologically and epistemologically more complex than what popular views of school inquiry suggest—views currently dominated by the idea of "the scientific method" as an unproblematic and universally applicable protocol (Bauer, 1992; Rudolph, 2003). Among the fundamental characteristics of discipline-based inquiry rarely incorporated into school science, at any level, are the use of theoretical models to generate meaningful questions for investigation and the subsequent use of argument to link evidence with the revision of these tentative models.

The third challenge for new teachers is that most of them, even those with degrees in science, are virtual strangers to authentic forms of inquiry. Much of what they learn about models and inquiry comes from their experiences as undergraduates; however, this coursework often consists of confirmatory laboratory activities (Trumbull & Kerr, 1993) and lectures in which instructors rarely discuss science as a discipline or how models and theory help generate new knowledge (Bowen & Roth, 1998; Duschl & Grandy, 2005; King, 1994; Reinvention Center at Stonybrook, 2001; Wenk & Smith, 2004).

Given these three factors, preservice education becomes a crucial time to challenge prospective teachers' understandings of the nature of scientific models and the role models play in the advancement of science. A number of recent studies have clearly shown that beginning teachers lack a deep understanding of scientific models (Crawford & Cullin, 2004; DeJong & Van Driel, 2001; Windschitl, 2004), but we know almost nothing of how they respond to instruction designed specifically to enhance their understanding of models and, in particular, of the key role these representations play in inquiry. The goal of the present study was to detail the design and outcomes of such an intervention. The study extends and problematizes what we know about teachers' understanding of models by examining how they create their own models, integrate them into empirical investigations, and generate arguments for the revision of these models—the very activities through which they are expected to mentor their own students.

Background

Role of Models in Knowledge Building

Scientific models are representations of how some aspect of the world works. Scientists create models in the forms of analogies, conceptual drawings, dia-

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grams, graphs, maps, physical constructions, and computer simulations as a means of describing and understanding the organization of systems, from cells to galaxies, and natural processes, from evaporation to predator-prey relationships.

Models are not unique, however, to the natural sciences. Disciplinarians in areas as diverse as geography, economics, technology, mathematics, and history use models to make sense of phenomena in their respective domains. The recent Gulf Coast hurricane disasters provide a gripping example of how models are used by members of different communities to inform, predict, and explain. In late August 2005, millions of Americans turned on their televisions to see an ominous whorl of color advance across the Gulf of Mexico toward New Orleans. But they were not watching the storm itself; what they were seeing was a model, a carefully constructed way of representing selected features of this natural occurrence (areas of changing wind velocity across a two-dimensional space). Scientists used similar atmospheric models to "virtually manipulate" variables such as air and water temperature in an attempt to predict the trajectory of the storm, the time of landfall, and its strength. After the storm, demographic models (in the form of coded maps) suggested that the most devastated human populations were also the poorest and helped explain, in turn, why evacuation models (systems of instructions directing how communication, law enforcement, and logistical support were to be mobilized) were based on faulty assumptions about people's ability to transport themselves out of harm's way.

Although models are ubiquitous in communities of inquiry, natural scientists use these conceptual tools in discipline-specific ways. In science, models are treated as subsets of larger, more comprehensive systems of explanation (i.e., theories); they help frame questions for specific investigations and act as referents in interpreting the results of such inquiries[1] (Darden, 1991; Giere, 1988; Kitcher, 1993). In practical terms, theory is testable only through models that situate hypothetical mechanisms within defined material contexts. Evidence for theoretical models involves using observations (for example, that sugar crystals dissolve faster in warm water than in cold) that support an explanation for which there are unobservable entities or processes (in this case, that heat causes water molecules to move faster, more easily breaking the intermolecular bonds of sugar crystals). In the course of inquiry, individuals use models to solve problems for which these representations appear to be adequate and revise explanatory models to account for anomalous data. Although different domains in science have their own fundamental questions, methods, and standards for "what counts" as evidence, they are all engaged in the same core epistemological pursuit: the development of coherent and comprehensive explanations of the natural world through the testing of models (Hempel, 1966; Kuhn, 1970; Longino, 1990). Even when research projects aim to collect data for descriptive purposes (such as cataloguing new species in a rain forest or mapping emerging star systems), this information is ultimately used by the science community to build explanations of how these patterns of data came to be.

Historical and contemporary cases of scientific inquiry suggest that it is all but impossible to consider a scientific problem without some implicit or explicit model as a frame of reference (Longino, 1990; Nersessian, 2005; Stewart & Rudolph, 2001). Even the self-asserted inductivist Charles Darwin, who claimed about his studies in the Galapagos that he worked "without any theory, collect[ing] facts on a wholesale scale" (Barlow, 1958, p. 120), was found by his biographers to have described, in private notebooks, proto-models for natural selection before he set out to gather data[2] (Gruber, 1974, p. 123). On the explicit side, James Watson and Francis Crick spent a great deal of time building scale models of DNA out of wire and wood, using the models to reason whether, among other things, the real molecule had a double or a triple helix structure (Watson, 1968).

The ways in which science uses models have implications for how such representations could be used in classrooms. For example, externalizing mental models via inscription or dialogue can help learners express their thinking, visualize their ideas in more organized ways, and test components of their ideas (Izsak, 2000; Mellar, Bliss, Boohan, Ogborn, & Tompsett, 1994; White & Fredericksen, 1998). Even mental models, because they can be explored extensively (run "in the mind's eye" to generate predictions and explanations), have been shown to aid both children and adults in experimentation and theory revision (Gentner & Wolff, 2000; Vosniadou, 2002). Students most successful at using models to guide investigations have developed understandings of the domains being represented as well as the nature of representations themselves (Lobato, 1996; Moschkovich, 1998). In other words, the importance of models in school curricula resides in the fact that they are not simply records of thought, but they shape thinking as well (Olson, 1994). Lehrer and Schauble (2004) claimed that "meta-representational competence [is] a general form of literacy" that has a wide application across school subjects (p. 672); however, they point out that even though models are widely presented in science, mathematics, and social studies classrooms, it is rare that instruction maintains an explicit focus on developing students' capability to evaluate the communicative value and design trade-offs for a variety of representative conventions, nor is it common practice for students to invent new ones for novel purposes.

Models and Inquiry in School Science

If we construe a central focus of inquiry for school-aged learners to be empirical hypothesis testing and take this enterprise to be consistent with real science, the following broad characteristics should apply:

1. An investigation should begin with an interest in some aspect of the natural world and an informed but tentative representation (i.e., model) of this phenomenon.
2. This model should include some aspects that are theoretical (i.e., represent unseen structures, processes, properties, or relationships).
3. The data collected to test the model should be used to identify patterns or relationships in the observable world.

4. Arguments should be constructed that attempt not only to validate the existence of these patterns but ultimately to support or refute claims about the unseen entities or processes hypothesized in the original model.

The first, second, and fourth characteristics differ in process and epistemology from the "scientific method" used in schools today (i.e., observe, develop question, create hypothesis, design experiment, collect and analyze data, draw conclusions, develop new questions). In much of school science, "observations" are directed by the teacher or guided by student interest but are rarely acknowledged as being influenced by preexisting theory or models. Consequently, the questions arising from such observations are seldom informed by even a modest understanding of the phenomenon. This reinforces the naive assumption that hypotheses are merely "best guesses" about experimental outcomes (Carey, Evans, Honda, Jay, & Unger, 1989; Sandoval & Morrison, 2003; Smith, Maclin, Houghton, & Hennessey, 2000) when, in authentic science, a hypothesis is considered a statement of how aspects of a declared model map onto real-world situations (Cartwright, 1983; Giere, 1991; Morgan & Morrison, 1999; Nersessian, 2002, 2005).

Students, then, are not often asked to understand the meaning and implication of "theoretical components" in a model. These classroom practices contribute to a lack of understanding about the nature of theories and models and increase the likelihood of content-free inquiry—that is, churning through the scientific method without understanding in any depth the phenomenon one is studying. Without the disciplined intellectual work of developing a tentative model at the outset, the "conclusion" phase of the scientific method becomes a conversation about relationships between measured variables but does not extend to what these results imply about underlying mechanisms.

The vast majority of the American science curriculum reinforces this canalized view of inquiry. For example, from their analysis of 468 inquiry tasks included in nine textbooks written for upper elementary and middle schools, Chinn and Malhotra (2002) concluded:

> The goal of simple [school] inquiry tasks is only to uncover easily observable regularities (e.g., plants grow faster in the light than in the dark), or the salient structures of objects, not to generate theories about underlying mechanisms. In short, the ultimate goal of most authoritative research is the development and revision of theoretical models. The goal of most simple inquiry is a Baconian gathering of facts about the world. (p. 187)

Similar findings for high school curricula were reported by Germann, Haskins, and Auls (1996). In sum, school science is not simply glossing over the details of real disciplinary work; rather, core epistemological discourses about the connections among theory, observation, evidence, and argument are entirely absent.

Authentic model-grounded inquiry for school-aged learners is indeed possible and need not involve complex science. Magnussen and Palincsar (2005) worked with a group of fourth graders who co-developed, with their teacher, a model of how light interacts with various types of materials. Through four iterations of data collection and model revisions, they moved from an intuitive toward a more scientifically accurate account of this phenomenon. Gains in integrated content knowledge and knowledge of inquiry through model-grounded investigations have also been documented at the middle school (see Schwarz & White, 2005) and high school (see Cartier, 2000, and Wells, Hestenes, & Swackhamer, 1995) levels.

Teachers' Understandings of the Nature and Function of Models

Despite the central role of models in science, the nature and function of these representations is not well understood by preservice or experienced science teachers. Justi and Gilbert (2002), for example, questioned 39 teachers from elementary schools, middle schools, high schools, and universities. Common across the participants was an awareness of the value of models in *learning science concepts* but not of their value in *learning about science*. Modeling, as an activity for students, was praised in theory but not widely practiced (see also Stephens, McRobbie, & Lucas, 1999). Van Driel and Verloop (2002) found that teachers rarely mentioned how models are used in making predictions or used as tools for obtaining information about targets that are inaccessible to direct observation. A study conducted by Harrison (2001) showed that some teachers had a comprehensive knowledge of models; however, only 5 of 22 participants expressed the belief that models could be used as thinking tools. Smit and Finegold (1995) found that prospective physical science teachers believed that models were useful only to help one understand, to explain complex or abstract ideas to others, or to demonstrate how things work.

There are only two accounts, of which we are aware, of attempts to reshape teachers' understandings of models. DeJong and Van Driel (2001) designed a preservice course to change participants' focus of teaching from the content of scientific models to the nature of models. Beginning chemistry teachers discussed articles from education journals on modeling, considered interventions for teaching about specific models, examined model-oriented curricula, and reflected on their ongoing experiences. Although the participants were advanced graduate students, most did not come to the understanding that models are used to make and test predictions.

In another study of secondary preservice teachers, Crawford and Cullin (2004) had participants design an open-ended investigation of a plant, soil, and water system and later build computer models of the relevant environmental phenomena. Of the 14 participants, 13 were initially classified as midlevel modelers. They could distinguish between ideas or purposes motivating a model and the model itself. In addition, they recognized how experimental evidence may show that some aspect of a model is wrong and needs to be changed. These individuals also conceived of models as representations of real-world objects or events. However, they captured spatiotemporal qualities rather than different theoretical views. Consistent with other studies, participants viewed models as representations used by "someone who understands" to explain to "someone who doesn't." All of the participants indicated that teaching about models was important, but their justification centered only on models enhancing students' learning of concepts. After the modeling experience in the course, participants shifted their thinking from models being used by someone to explain an idea to another to the model being considered by a "user" to understand the phenomenon him- or herself. Overall, however, no participant moved from a mid-level understanding to an expert level. Moreover, there was almost no change in participants' beliefs regarding the importance of teaching about scientific models or in their intentions to teach about them.

A final study shed light on secondary preservice teachers' understandings of models not by asking about models themselves but through an analysis of how teachers conducted empirical investigations during a methods course (Windschitl, 2004). Most of the 15 participants subscribed to a "folk theory" of scientific inquiry in which models played no discernible role. Some facets of this folk theory were congruent with authentic science, but others were misrepresentations of some of the most fundamental aspects of scientific inquiry. For example:

- Background knowledge may be used to suggest ideas about what to study, but this knowledge is not in the form of a theory, explanation, or model.
- Empirically testing relationships and drawing conclusions about these relationships are epistemological "ends in themselves."
- Models or theories are optional tools used only at the end of a study to help explain results.

Almost entirely absent from written artifacts and interviews were references to the epistemological bases of inquiry—talk of claims and argument, alternative explanations, development of models of natural phenomena, and so forth. Most participants, for example, based their inquiry questions not on a hypothesized system but on what seemed interesting, doable, and novel (e.g., bubbling car exhaust through water to see how acidic it becomes or comparing plant growth with and without exposure to music).

These modes of thinking are consistent with what Driver, Leach, Millar, and Scott (1996) referred to as *relation-based reasoning*. This type of reasoning is characterized by a focus on correlating variables or identifying a linear causal sequence, which typically requires an intervention to seek cause or predict an outcome. The nature of explanation for relation-based reasoning, however, refers only to connections between features of a phenomenon that are observable (e.g., sugar crystals of smaller size will dissolve faster in water than will larger crystals) without using those connections to argue about underlying causes. This reasoning was pervasive in the preservice teachers' inquiries. None of the 15 preservice teachers employed the most advanced form of scientific thinking: *model-based reasoning*. This perspective takes inquiry as an empirical test of a model or theory. The nature of explanation associated with this perspective is that models and theories are conjectural, that explanation frequently involves coherent stories that posit unobservable processes, and that explanation involves discontinuity between observation and theoretical processes. In using model-based reasoning, one's argument not only includes querying data and the way data are analyzed but, more important, challenging aspects of the model that underlie the study—such as assumptions made about the model, challenges to its coherence, and appeals to alternative explanations.

In summary, studies of how teachers talk about models reveal consistent misconceptions and suggest that these ideas remain largely unresponsive to instructional interventions. Teachers think of models as pedagogical aids but generally do not recognize the crucial role of models in thinking theoretically or guiding the generation of new knowledge. Consequently, they show little intention of using models in these ways with their students.

A Theoretical Framework for Instructional Activities With Preservice Teachers

Informed by previous attempts described in the literature to foster model-based thinking in teachers and by what is known of typical school science learning experiences, we designed a secondary science methods course for preservice teachers based on a broad instructional approach known as *productive disciplinary engagement* (PDE), an orientation articulated by Engle and Conant (2002). They suggested four principles that should underlie learning environments in which the aim is to foster participation in material and discursive activities that characterize the work of scientists (specific course activities are described subsequently).

The first two principles are *problematizing content* and *giving students authority*. Problematizing content is accomplished by encouraging students to pose problems, hypothesize, challenge ideas, and question rather than expecting them to ingest concepts or procedures (Cognition and Technology Group at Vanderbilt, 1997; Hiebert et al., 1996; Krajcik, Blumenfeld, Marx, & Soloway, 2000; Warren & Rosebery, 1996). Giving students authority means that they are producers of knowledge with ownership over it rather than being consumers of other people's ideas. Students are given an active role in defining, investigating, and resolving problems (Ball & Bass, 2001; Cobb, Gravemeijer, Yackel, McClain, & Whitenack, 1997; Lampert, 1990).

In considering how to incorporate these two principles into the design of our intervention, we recognized that preservice teachers typically understand inquiry from highly structured learning experiences and rely on the scientific method to frame their thinking. We sought to problematize their conceptions of atheoretical inquiry by requiring that they conduct an empirical investigation predicated on a model they had to generate (or adapt) themselves. We wanted to give participants the authority to select the topic for their inquiries, to construct their own models, and to conduct their own investigations. We also noted from the literature that teachers maintain a view of models only as pedagogical aids and that even after interventions, they remain unlikely to teach about scientific models in their classrooms. We planned to challenge our participants' beliefs about models being useful only to teach about concepts by helping them develop ways to use common technologies, materials, and activities to teach young learners about the *nature and function* of models.

The third principle of PDE is *holding students accountable to disciplinary norms*. Students are held accountable to practice within the bounds of the relevant discipline; that is, they recognize constraints of how questions can be framed, abide by the canonical methods of investigation, and use appropriate forms of argument (Resnick & Hall, 2001). Because the literature indicates that teachers are rarely exposed to conversations about science as a discipline, we intended to involve participants regularly in talk about the articulations among theory, models, observation, and evidence. Some of the discursive norms to which we held them accountable were matters of expression—for example, we did not allow students to suggest that "data could prove" a claim. Other norms were institutionalized into the coursework; for example, in the long-term inquiry project, we required that students develop culminating public arguments in which their data had to be used specifically to support or refute aspects of their initial model.

The fourth principle is *providing relevant resources*. Resources include basic necessities such as having enough time to pursue a problem in depth (Collins, 1998; Henningson & Stein, 1997), having access to key materials and information necessary to complete a task (Roth, 1995; Windschitl, 2001), and being exposed to conceptual frameworks that may facilitate reasoning about a problem or guide complex procedures (Lampert, 1990; Sohmer, 2000). In identifying useful resources, we considered that inquiry experiences by themselves have failed to foster greater understandings of the discipline (Meichtry, 1992; Sandoval & Morrison, 2003; Windschitl, 2004) and that explicit guidance about the methods and epistemology of science has proven effective for various types of learners (Abd-El-Khalick, Bell, & Lederman, 1998). We incorporated textual resources into the coursework that explicitly addressed the roles of theory, models, empirical work, and argument in authentic science. And, because conversations about models are often too abstract to be meaningful, we provided multiple occasions during which conversations about models were contextualized by the students' own material investigations and by computer simulations of phenomena that operated on underlying theoretical models.

While the principles behind PDE prescribe characteristics conducive to disciplinarily grounded learning, they do not suggest a reasonable progression of activity that could facilitate the development over time of more sophisticated ideas about models and inquiry. The literature indicates that conceptual change in teachers is difficult to achieve and suggests that interventions have been too brief or have not provided learners with multiple opportunities to engage in the discourse of modeling within a variety of investigative or pedagogical contexts. In light of this, the learning activities included in the study were purposefully sequenced to involve participants early in structured discourse around specific norms of inquiry and specific scientific models used in class. Gradually, the activities placed more responsibility on the participants to think generatively about a wider variety of models and to connect the use of models with strategies for instruction. The latter activities encouraged them to think about the nature and functions of models that transcended specific contexts.

Questions and Method

Our research goal was to document the influence of strategically designed instructional experiences as well as the influence of past investigative experiences on participants' understandings of models and scientific inquiry. We used a qualitative multicase study approach (Creswell, 1998), incorporating observations, student-created artifacts, informal interviews, field notes, and questionnaires. The study addressed the following questions:

1. In what ways does an instructional focus on models and model-based investigations influence beginning teachers' conceptions of the role of models in inquiry?
2. In what ways does an instructional focus on models influence beginning teachers' plans to use models in their own teaching?
3. How do beginning teachers' understandings of scientific models influence their ability to create and use models as the basis for authentic investigative experiences?
4. How do previous investigative experiences shape beginning teachers' thinking about models and their role in inquiry?

Participants and Context

The 21 participants in this study were students in a teacher education program at a public university in the northwestern United States, all enrolled in a secondary science methods course. All candidates enter the program with at least a bachelor's degree in an area of science, and they graduate with a master's in teaching degree. The course was two quarters in length and was taught by the first author. In previous years, only 20% of students in this course had reported opportunities to design and conduct independent investigations during their precollege and college careers. In response to this perennial lack of research experience, students in this study were asked to engage in an independent inquiry as a major course project. Participants' research projects encompassed a wide range of interests, including evaporative cooling, the effects of dissolved materials on the buoyancy of liquids, the effects of radiation on seedlings, and a variety of other topics. Although the course included other learning activities, the inquiry project was their long-term source of engagement with models and inquiry.

We wish to note that such complex, long-term projects are learning activities in themselves, but at the same time they are influenced by other course-related experiences. As such, they provide data about the interaction of existing ideas with new conceptions fostered by instruction. Most participants, in fact, did not begin their project for several weeks, after a number of other model-related course experiences had occurred. We believe that the breadth of data collected helps to distinguish the relative influences of previous experience from the course's instructional scaffolding.

Progression of Course Activities and Their Relation to the Theoretical Framework

Most of the activities that were explicitly aimed at developing participants' understanding of models and their role in inquiry took place in the first 11 weeks of the two-quarter course. In the following, these activities are described in chronological order (Figure 1). Descriptions include parenthetical references to the design principles of PDE where appropriate.

Immersion Experience

During the first class, participants were "immersed" in an investigative experience. In small groups, they were given a number of live fish and guided through activities that prompted them to make observations, pose their own questions, collect data, and present results to peers. During the debriefing, students were asked when this instruction would be appropriate in the classroom and what the limitations as well as the benefits were for this type of activity (PDE features: giving students authority and problematizing content). Although this initial activity was structured, to a degree, by the available materials, it was a necessary instructional choice given that most preservice teachers have little experience in doing investigations of any kind (Roth, 1999; Windschitl, 2004).

Introducing the Inquiry Project

During the second class of Week 1, the instructor introduced the major project for the fall quarter. Students were asked to develop an authentic scientific investigation individually or working in pairs, complete it, and present the results to peers by the end of the 11-week fall quarter. During this time, students would maintain a journal in which they were to record the trajectory of their ideas, their day-to-day activities associated with the project, and reflections about the inquiry process. To link pedagogical thinking with the inquiry project, they were asked to base their inquiry on a "cookbook" or confirmatory lab exercise found in a science textbook of their choice (PDE feature: problematizing content) and transform the pseudo-inquiry into an authentic investigation.

Three key requirements of the project were developed in light of previous studies in which students universally failed to use theory or models to frame their inquiry questions. First, after selecting the initial textbook activity, participants would have to read at least four "college-level" information resources on the topic. Second, participants would have to integrate infor-

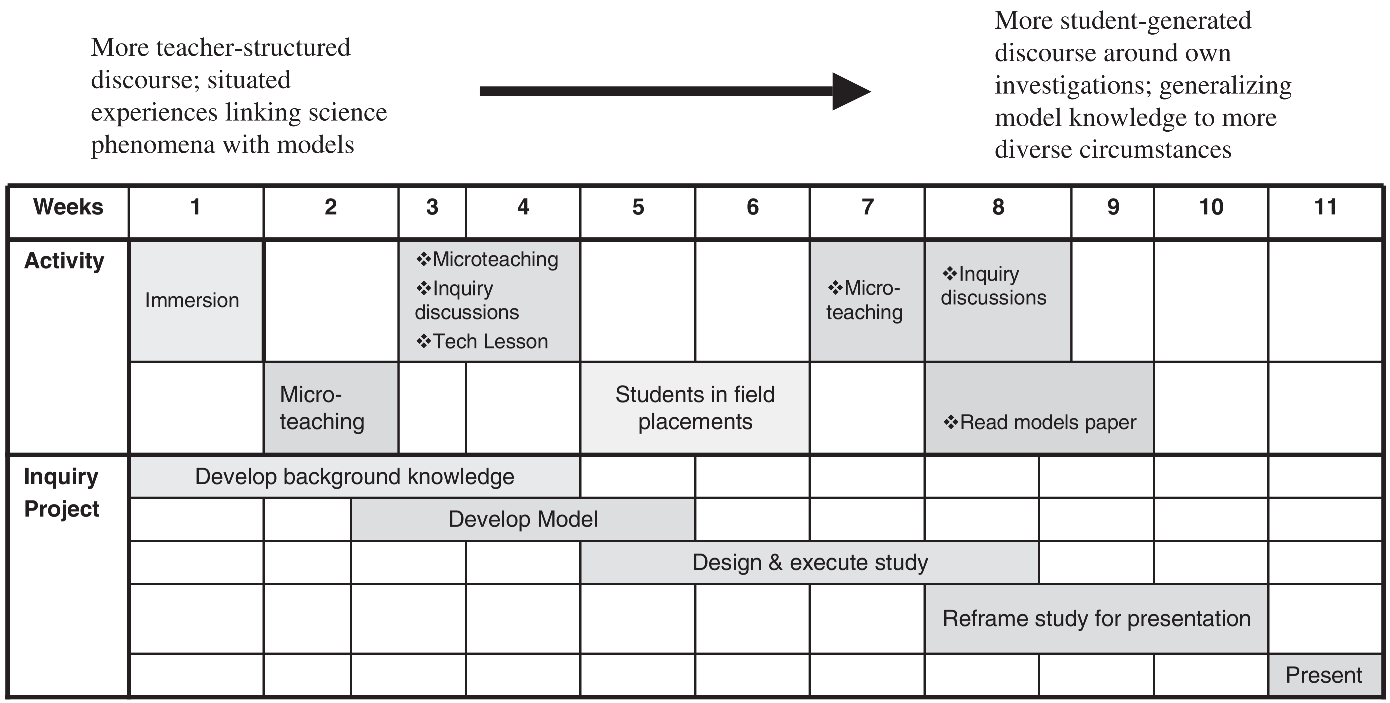

Figure 1. **Timeline of activity for first 11 weeks of course.**

mation from the background reading into a scientific model. They would then be required to identify which aspect of their models they would test in the investigation. Finally, on completion of their data analysis, participants would have to use their evidence to argue for support, elaboration, or refutation of associations in their original model (PDE feature: holding students accountable to disciplinary norms).

Participants with similar project interests were asked to form inquiry groups of five or six. In this way, members could share background reading material, brainstorm about how to extend the basic inquiries, and engage in task-specific discourse about the scientific models they were working from and toward (PDE feature: providing relevant resources). Participants within these larger groups were still responsible for completing their own projects individually or in pairs.

It is important to note the differences between cookbook science and the organization of this investigative project (we see it as a case of "stricture vs. structure"). In cookbook exercises, the question is given to students, the methods are specified in behavioral detail, and the final outcomes are known ahead of time. None of these conditions were imposed in the inquiry project. Students were asked to follow methodological practices and adhere to epistemological norms that emulated authentic science. How they addressed these requirements were matters of interpretation, judgment, and application.

Introducing Models Through Micro-Teaching

Beginning in the third week of the quarter, the instructor demonstrated a series of three teaching strategies that participants first engaged in as "students" and then executed themselves in micro-teaching sessions of between 12 and 30 minutes. The second of these instructional strategies, labeled "guided exploration," focused on the development of conceptual models by learners through engagement in semistructured activity. The first author led the activity, which involved students in using pulleys, rope, masses, and spring scales to create a model, in the form of rule-based statements, of mechanical advantage (PDE feature: providing material and conceptual resources).

After working with the pulleys in small groups, participants pooled their data and were asked to develop a rule that would consistently describe the relationship between effort and load based on the pulley configurations. Several hypotheses were suggested by the participants (e.g., number of pulleys, total number of ropes). Embedded in the pulley activities were discussions about systematically organizing data, developing hypotheses about relationships, and using data as evidence to support or refute a hypothesis (PDE feature: accountability to disciplinary norms). Midway through the class discussions, the instructor inserted the term *model* in the group conversation. Later the instructor explicitly asserted that participants had created a model, based on evidence, that was represented as both a verbal rule and a mathematical expression. Without prompting, several participants suggested that the model was useful for predicting how pulley systems in elevators or cranes might work.

Using Technology as a Context to Think About Models

Later during Week 3, in the technology section of the class, students explored computer-based simulations. Simulations are designed to teach about a natural system by allowing learners to manipulate variables in the system and observe the results through visual feedback generated in real, accelerated, or slowed time (Alessi & Trollip, 2001). The instructor began the conversation by indicating that these applications presented "dynamic representations of underlying models." At this point, models were formally described for the first time as a set of hypothesized relationships among objects, events, and processes. Participants were shown a human cardiovascular simulation and asked to discuss what the underlying model was in terms of related propositions.

Participants then explored two simulations, altering key variables and observing changes in the system. One was a "survival of the fittest" biology simulation, and the other was an astronomy application (PDE feature: providing relevant conceptual and material resources). For homework, participants addressed four questions/tasks that probed their understanding of the models presented (for example, select one simulation from today, identify one model, and state it in generalized form, usually as a rule or set of connected rules). To link pedagogical thinking with an analysis of this software (PDE feature: problematizing content), participants also responded to three questions regarding how they could use the simulations to teach about scientific models (see Appendix A).

Reading and Discussion of Models and Argumentation Paper

During Weeks 4 to 7, students worked independently on their inquiry projects and spent part of that time in schools doing classroom observations. In Week 8 of the class, participants read a paper (written by the authors of this article) that provided a comprehensive description of scientific models, offered a variety of examples of forms that models could take, and positioned the development of models as a central activity of the discipline (PDE feature: providing relevant conceptual resources). The second part of the paper provided examples of how authentic scientific investigations begin with implicit or explicit models that form the basis of testable hypotheses and explained that the goal of inquiry is not simply to identify relationships between variables but to use such empirically validated relationships to revise the original model (PDE feature: accountability to disciplinary norms).

Final Presentations of Investigations

As fall quarter drew to a close, participants' independent inquiry projects were being completed, and they prepared to present their work to peers. This required them to reflect on the coherence of their investigation and consider how to present the evidence and arguments. During Week 11 of the quarter, participants shared the results of their investigations using presentation software. They were required to have, at a minimum, eight slides that described (a) key background information they had used to develop their initial model, (b) a representation of their initial model, (c) their research question, (d) methods, (e) a set of tables or graphs representing their data, (f) a final claim based on empirical evidence, (g) assumptions they made in designing and conducting the study, and (h) arguments for a revised model based on investigative findings (PDE features: providing relevant conceptual resources and holding students accountable for disciplinary norms). During the presentation, other participants were asked to pose questions about the nature and quality of the evidence and the use of evidence to support arguments for or against various changes in the final model.

Data Sources

Eight data sources were used in this study. The first was a questionnaire given to participants during their first class meeting that elicited ideas about the nature of science models (e.g., "What kinds of things do scientists make models of?" and "What is the relationship between the model and the 'real thing'?"), the function of models (e.g., "What is the purpose of scientific models?" and "Would a scientist ever change a model? Why or why not?"), and the use of models in instruction (e.g., "Is teaching about models important in your area of science? Why or why not?").

The second data source was participants' inquiry journals (as described in the previous section). The third source was transcripts from whole-group and small-group conversations during classes. The fourth was participants' responses to the model-based technology assignment (as described in the previous section). The fifth was videotapes of participants' presentations of their investigations. The sixth was a questionnaire given at the end of the two-quarter course (see Appendix B) that elicited participants' ideas once again on the nature of models, the role of models in science, and the potential uses of models in teaching science.[3] The questionnaire also asked participants to describe their experiences with inquiry before entering the program. This question was asked "postcourse" because previous studies we have conducted indicate that participants are better able to recall such experiences after several months of course conversations around inquiry opportunities in school settings. The seventh data source was participant-developed unit plans to be used for student teaching the following fall. The final data source was a series of informal conversations with participants that took place over a period of 6 months. These conversations provided additional information about participants' opportunities to do various forms of science research in and out of school settings.

Data Analysis

Nature and Function of Models Questionnaire

Participants' understandings of models were determined from the questionnaires administered at the beginning and the end of the study by triangulating responses from groups of questions. "Understanding models" was divided into two dimensions: the *nature of models* (e.g., what they are, what distinguishes them from phenomena, what is necessary to create them) and the *function of models* (e.g., the use of models in science, the possibility of multiple models of the same phenomena). For both categories, participants' descriptions were rated as 1, 2, or 3. Ratings of 1 indicated views least congruent with those of experts, and ratings of 3 indicated views most congruent with those of experts. The ratings were scaled to the range of participants' responses. That is, ratings were relative to others in the participant pool. In the broader population of science learners of all ages, for example, there are individuals who would have held less sophisticated conceptions of the nature and function of models than participants in this study with a ranking of "1" in either category.

For the "nature of models" category, those participants scoring a "1" described models exclusively as pictorial or physical replications of objects suggested as real that may or may not be accessible to direct observation (e.g., plastic skeletons, drawings of DNA, solar system models made of foam spheres). These participants did not refer to processes, events, or systems as being the subjects of models. Participants scoring a "2" indicated that models could be representations not only of objects but of observable processes or systems (e.g., fluid flow in a functional watershed mock-up, fruit flies acting as model organisms). Those scoring a "3" transcended the empiricist perspective and described models as systems whose key features include theoretical entities or processes (e.g., kinetic models of molecular motion, protein folding); these individuals saw models as inherently fallible, not only because they are a result of "best guesses" using available data but because of the conceptual and creative nature of building theoretical models.

For the "function of models" category, those scoring a "1" indicated only that the role of models was to simplify, illustrate, or allow one to examine closely something that was not easily accessible to direct inspection—essentially "to show." Those scoring a "2" said that models are used to facilitate the understanding of an object, process, or system of relations. Those who scored a 1 or 2 presented a generally unproblematic view of models as representing an objective reality, and the ideas of "illustration" and "helping one to understand" were described in terms of an expert using models as tools to communicate the details of real objects or processes to a learner. Participants scoring a "3" suggested a more problematized view of models, saying that they could be used to predict phenomena or that models were the basis for thinking about theoretical systems. For those receiving a rating of 3, models were tools for advancing scientific thought rather than exclusively trailing it as a "product" of experimentation.

We rated participants who made statements indicating two different levels of understanding for the nature or function of models at the higher of the two levels (see, for example, Cash's statement about the nature of models in the Findings section). Ratings were made independently by the authors. Minor revisions were then made to the rating criteria, and all participants were assessed again with a resulting correlation of .87 between raters. In the case of nonmatching scores, agreement was arrived at through negotiation and examination of additional data sources.

Previous Investigative Experiences

From the interview data, participants' histories of investigative experiences were rated as "extensive," "some," or "little/none." Those grouped in the "extensive" category reported involvement in authentic research activities as undergraduates, as graduate students, or in a career. This involvement included participation in framing questions, designing studies, and collecting and analyzing data. Those grouped in the "some" category reported two or three instances of independent or guided inquiry during their K–16 schooling or in a science setting after graduation. This included work restricted to technical tasks (collecting and analyzing data, following protocols designed by others). These individuals were not involved in posing research questions or in research design. Those grouped in the "little/none" category reported no instances of independent or guided inquiry throughout their K–16 schooling, very few instances of structured inquiry during school, and no work-related experiences involving research.

Journal and Final Presentation Analyses

Data analyses for the inquiry journals and final presentations were done in parallel and broken down into three parts. The first was characterizing the nature of the initial scientific model generated by participants. Participants developed their models from background readings and were asked to use them as the basis of their investigations. These models were initially characterized along three dimensions: causal or descriptive, simple or complex, and theoretical or empirical. Because of the generative and novel nature of participants' tasks, these descriptions could not always be categorically applied (for example, many initial models combined elements that were empirical and theoretical); rather, they served as broad guides for further analysis.

The second part of the analysis of the journals and presentations assessed the relationship between participants' initial model and their investigations. This analysis was based on the work of Driver et al. (1996), who described three increasingly authentic forms of science inquiry. The first is "practical activity," which involves simply making phenomena happen so that consequent behavior can be observed. In this type of activity there is no intention to explain, only to describe. The second is an empirical evaluation of a formally stated hypothesis. This involves characterizing relationships between variables. Theory is portrayed only as a correlation between stated variables, and the aim of empirical evaluation is to demonstrate that certain conditions are related to outcomes without reference to unobservable mechanisms (for example, that salt speeds up rusting). The third level of inquiry is empirical evaluation of an explanatory theory. This form of reasoning involves modeling and posits a theoretical system that relates underlying properties of the system to observable changes in variables that need to be explained.

The third part of the analysis of journals and presentations examined the aims of the arguments that participants invoked when presenting their findings to peers. In most cases, participants used data as evidence to characterize relationships between observable/directly measurable variables rather than to make claims about underlying mechanisms. Data from the classroom transcripts, informal interviews, and technology assignments were used to supplement emerging hypotheses developed in the primary analyses of the questionnaires, journals, and presentations.

Findings

Participants' Initial Understandings of the Nature and Function of Models

Participants varied dramatically in their initial descriptions of the *nature* of models (see Table 1 for representative cases). Numbers of participants in each rating category and examples of questionnaire responses follow. Of the 21 participants, 7 received a rating of 1.

> You have to consider what you think are the most important details which you want to share because a model needs to be informative, not overwhelming . . . the model needs to be accurate in its portrayal . . . the relationship between a model and the real thing is what the designer wants the viewer to see. An arm can be shown as different tissues, muscles, or bones depending on the perspective that one wants to share. (Emilla)

> [A model] has to be accurate, has to have the right size to scale, accurate movement or moving parts, etc., and the different parts have to be identified clearly. (Gregor)

Seven participants received a rating of 2.

> They can make models for processes (i.e., photosynthesis or digestion) or for representative study such as model organisms (i.e., Drosophilae for genetics). (Amber)

> Scientists make models of different systems or processes that occur in the natural world that can be difficult to observe or examine. (Verna).

Seven participants received a rating of 3.

> A model is a set of actions based upon proven theory that gives reproducible results when trying to explain why something works the way it does. The "real thing" in terms of fact or truth does not relate to a scientific model because science cannot be proven as truth. (Cash)

> [Models] must exist for a clear purpose, i.e., Hardy-Weinberg, whose assumptions exist to be broken. (Deanne)

Regarding the *function* of models, five participants received a rating of 1.

> Models give a representation of how a thing operates in the natural world. (Yvonne)
>
> The purpose of a model is to examine closely. (Carmen)

Seven participants received a rating of 2.

> Models are to simplify or facilitate scientific learning. (Amber)
>
> Scientists make models to help them explain important concepts in science. (Sinda)

Finally, nine participants received a rating of 3.

> If a model didn't predict what scientists observed about a dynamic system, then the model would have to be changed. (Jeanne)
>
> A model can be used to test theories about a certain part of the natural world. (Colleen)

Rating participants' responses presented several challenges, one of which centered on statements that models could be used for "explaining things." From the context of other statements made by participants, we determined that explanation for some meant that a model was a way for a more knowledgeable individual to help a less knowledgeable individual understand a broadly accepted way of looking at a particular phenomenon. Others, however, spoke of models serving as temporary explanatory frameworks, in the sense that the science community uses models as conceptual aids to consider the fit between observation and theory. This latter perspective transcends the notion of both an objective reality and naive empiricism and is more congruent with an expert view of models.

Combined scores were calculated for each participant, and this composite was referred to as "understanding of models." Eight participants scored a total of 3 or less, 4 participants scored 4, 2 participants scored 5, and 7 participants scored the maximum of 6. We further classified participants scoring 3 or less as "low understanding" ($n = 8$), those scoring 4 or 5 as "moderate understanding" ($n = 6$), and those scoring 6 as "high understanding" ($n = 7$). Interestingly, there was no relationship between participants' research experience and "understanding of models" scores: Of the 8 participants in the low understanding group, 3 had extensive research experience. Conversely, 4 of the 11 participants with little or no research experience had expert or near expert understandings of models.

There was a strong relationship, however, between participants' initial level of understanding of models and their belief that models could be used to teach the nature of science (i.e., that instruction on models could provide valuable lessons about the constructed and tentative nature of theories, how

Table 1

Case-Level Display: Selected Participants' Precourse Understanding of Models, Ordered by Increasing Congruence With Expert View

Participant	Examples	Need to Know to Create Model?	Pedagogical Importance?	Additional Descriptions
Emilla (nature = 1, function = 1)	Replicas, 3-D plastic figures	Need important details, must be accurate, attend to spatial placement, shape	To teach concepts	Could have more than one model based on different viewpoints (muscular vs. skeletal system)
Carmen (nature = 1, function = 1)	DNA, crystals	Know angles, colors, textures	"Cannot think of an answer"	"Models are made of things scientists can't see with their eyes"
Gregor (nature = 1, function = 1)	Atoms	Size and scale and moving of the parts	To teach concepts	"We can't see an atom, but we can make assumptions about how it looks, then we make models we can see and touch to help us understand more"
Yvonne (nature = 2, function = 1)	Plate tectonics, solar system	Consider what is known and what is conjecture; what is accomplished by making model?	Confused as to what a model is, how it could be used	"I have never heard of these things as 'models'; my science classes presented these things as works in progress"
Amber (nature = 1, 2, function = 1, 2)	Photosynthesis, drosophilae as model organism	More similarity to real thing is desirable, know which aspects "match up with the real thing"	To teach concepts by simplifying them	Purpose of model is to simplify or facilitate learning

Sinda (nature = 2, function = 2)	Plate tectonics, earthquakes	Need to know purpose of model; must know variables, cause-effect relationships	To teach concepts	"I don't have a good idea of what a model is, how to separate a model from phenomena"; models are put into action under ideal circumstances
Jeanne (nature = 3, function = 1, 3)	Systems, dynamic processes	Must know steady state of system; "can I know three variables and get the fourth?"	Once you have determined phenomena, you can develop a model yourself	"You can use a model to think with"; "if you are concerned with accuracy you want more variables, but with general behavior you want a simpler model"
Molly (nature = 3, function = 2, 3)	Kinetic model of molecules	Create model by doing observations, then see if they fit; should equate theory with model	Important to teach about models; should not be confused with reality; they are not learning "truth," but way to think about data	Models can be a way of thinking about the world
Buddy (nature = 3, function = 3)	Ecosystems, human behavior	Must be testable, incorporate all of the variables that affect system's behavior	Use to extend to new situations, e.g., plate tectonics to talk about geological processes on other planets	Elegance is important; simpler models may explain better than complex ones; models make predictions about systems under previously unobserved conditions

they are conceptualized and tested, etc.). Of the 9 participants with the highest understanding scores, 6 suggested that models were important, in and of themselves, to teach about. One participant, Molly, said that "it is important for students to understand that what they are learning is not 'The Truth' but that it might be a convenient and effective way of thinking about something." Another participant, Steve, mentioned that students should learn how to use models and be able to ask the kinds of questions that would help them develop their own models. In contrast to these views, the 12 lowest-scoring individuals claimed that models were important to use as a vehicle to teach about experientially inaccessible concepts such as atomic structure, but none suggested that the idea of models or modeling was of value.

Although only a third of the participants could talk about models in relatively sophisticated ways on the precourse questionnaire, a different story emerged 2 weeks later during the technology section of the class, when participants had experiences with several computer-based models (evolution and astronomy simulations). Even those individuals whose precourse descriptions of models were least congruent or complete with regard to the scientific perspective were able to identify conceptual models within the simulations, describe how these models could predict a variety of phenomena in contexts beyond those used within the simulations, and point out limitations in the models that would compromise the data-theory fit under certain real conditions.

Yvonne, for example, who had a composite score of only 3 for understanding models, was able to talk about models as tools for explanation and prediction. She accurately described the model within the natural selection simulation as a set of interrelated propositions: "Mutations allow for new types of organisms to be created. When natural selection occurs at random, those new mutated organisms may become a larger percentage of the population." She made valid suggestions about how the model in the simulation could be applied to a wide variety of circumstances and serve to predict some natural phenomena. She remarked that "it might be helpful to use these [model] statements to understand why there are so many different kinds of fruit flies in the world." Amber, who also had a composite score of 3, used the contextualized example similarly to talk about models in more sophisticated terms. She interpreted the underlying model as follows: "Living things that are better able to evade predators have a greater chance at survival, and therefore reproduction." She understood that the model was limited in that there are not several but many factors operating simultaneously that influence survivability in ecosystems. She correctly surmised that the model could predict how size and camouflage affect both predator and prey. She believed that the model could be faulty because it "did not change"—that is, if environmental conditions changed, the model would not predict outcomes accurately.

Participants' Incorporation of Models Into Inquiry

For their independent inquiry project, participants were required to use background readings to develop a tentative model, state it explicitly, and use the model to develop a research question. Their artifacts for the project were assumed to have been jointly influenced by previous investigative experiences and the instructional scaffolding of the methods course. The following sections summarize (a) the nature of the initial models, (b) the ways in which the investigations related to these original models, and (c) the ways in which empirical evidence was used to formulate arguments after the investigations.

Types of Models Created by Participants to Frame Their Inquiries

What was noteworthy about the initial models generated by participants was the sheer diversity of how they were expressed. They were categorized into five types. Seven participants portrayed their models as *causal systems or event chains*. These included not only observable phenomena but also the underlying mechanisms. Gregor and Marla, for example, presented a model of evaporative cooling that described phase changes (liquid to gas) at the molecular level, which in turn provided the theoretical basis for observable decreases in temperature.

Six participants portrayed their models as *descriptive systems,* some of which implied causal associations among parts of the model but did not explicitly express causal mechanisms. For example, two participants who were working together identified Newton's law of cooling as their model. Laws, by definition, describe regularities but do not specify theoretical processes; as such, they cannot themselves be used as the object of testing and revision, but they can be used as a tool to predict phenomena under various circumstances.

Four participants expressed their models as *hypotheses* (Penny, for example, wrote: "Salt stabilizes the ocean in liquid form"). While hypotheses as statements of conjecture can be considered simple models (and are necessary components of most investigations), they lack a larger network of relations among conceptual entities and processes that give them meaning or applicability across contexts. The investigator can conduct empirical tests to determine whether the hypothesis is supported or not, but if the hypothesis is not derived from a larger model, the results cannot help refine an explanatory account of the phenomena.

Two participants portrayed their models as *a series of statements related to a central topic,* but the statements themselves were not related to each other. Sinda's model, for example, involved water retention of various planting media; her model was a series of statements about why each type of media would be likely to retain water (e.g., "Spongier materials like cedar chips will have a greater water-holding capacity" and "Lava rock will absorb more water than gravel because it is porous").

Two participants drew models not of the phenomena to be investigated but of *the experimental procedure itself.* Serena, who did a study of handwashing's effect on bacterial contamination, drew out a flowchart linking her research question with the dependent and independent variables, the procedural details of data collection, and placeholders for the results of her data analysis.

In classifying these models, a dilemma arose about identifying what participants understood to be part of their models. Many who had sparse "theoretical" models (three or four interrelated concepts) or simple descriptive models had included additional relevant information in their presentations or in their journals about the central phenomena but labeled it separately from the model as "background information." This information could have been integrated into the stated models to create richer networks involving theoretical mechanisms. Verna, for example, studied the effects of grapefruit seed extract on bacterial growth. Her model was a diagram of experimental procedure rather than a set of interrelationships among conceptual entities. In her final presentation, however, she presented as "background information" the results of previous studies that showed how the extract broke down the cell membranes of the bacteria. Clearly she understood something of the underlying mechanism of the antibacterial agent, but she did not recognize it as a key component of her model. Similarly, Buddy, whose model of changes in soil moisture included observable processes such as evaporation, had listed as background information more fundamental causal mechanisms such as particle adhesion, hydration, and capillary action, but he did not include these mechanisms in his model. In characterizing the types of models constructed by participants such as Verna and Buddy, we adhered to an analysis of what they identified as their initial model and did not make inferences that they intended their background information to be part of their model.

Participants' attempts at creating their own models revealed two important features of their thinking. The first is that, despite being able to recognize and talk about existing models with some degree of sophistication (especially in reference to the specific models used in the technology section of the course), participants were unfamiliar with the process of creating their own models, particularly the kinds of theoretical models that form the basis of empirical investigations. Second, the models produced by participants were not necessarily reflections of their knowledge about the phenomena of interest. Key conceptual entities and relationships were frequently expressed in participants' journals and presentations but were not incorporated into their models. This lack of experience in developing models had implications for how participants attempted to use their models as the basis for data collection, as the following section illustrates.

Participants' Attempts to Relate Models to Their Investigative Questions

Ideally, the models generated by participants should have been a focused and coherent set of relationships based on background information, including certain theoretical relationships that could prompt interesting and testable questions. This was the case, however, for only 2 of the 21 participants. These participants (Jeanne and Colleen) created models that suggested theoretical processes and then designed an investigation to observe variables under contrasting conditions to make claims about theoretical processes (exemplifying *model-based reasoning*). Colleen, for example, created a model of seedling development that described the conditions necessary for vigorous shoot and root growth. Her model included the theoretical assumption that there was a limited amount of stored food energy that could be devoted to root growth and that this energy would be used up with constant reorientation of seeds to gravity. Her study involved comparing rye grass seedlings rotated around a horizontal axis every few days against a control group of seedlings as a means of assessing whether her conjectures about theoretical processes were supported. In her project, Jeanne studied the absorption capacities of different types of fabrics. In her initial model, she proposed a causal system including observable and theoretical processes (how pores in the fabric, molecular structure, and surface area affect fabric absorbency). Jeanne was the only participant to explicitly test for a theoretical interaction that was not common knowledge—the differential affinity of certain liquids to hydrophobic (water-repellant) and hydrophilic (water-attracting) ends of fibers.

The most common way in which the remainder of the participants used their models as a basis for investigations was to identify a known relationship between two observable variables within the models and run empirical tests to determine the specific nature of these relationships (i.e., strength of covariance, differences between groups, changes in variables over time, etc.). Because these relationships were never used to support or refute aspects of participants' models, the reasoning behind these approaches was characterized as *relation based*. Carmen's model, for example, included a relationship between the breakdown of vitamin C in orange juice and storage temperature. Her investigation was designed to show the drop in vitamin C over time at various temperatures. Although her initial model included theoretical mechanisms, her investigation was designed to assess the specific character of known empirical relationships rather than linking these relationships with underlying causes. Seven participants (Molly, Lucille, Carmen, Marla, Yvonne, Gregor, and Michael) "tested their models" in this manner.

Two participants who worked together (Phillip and Cash) used their model differently. Because they chose an existing descriptive generalization (Newton's law of cooling), there were no theoretical relationships between entities to test. Instead, they used this mathematical model as a tool to reason about a practical question: "If you have a long walk across campus, is it better to put the cream in your coffee when you first buy it or when you arrive at your destination?" This investigation tested the congruence between what the model would predict and the empirical outcomes under contrasting conditions.

The remaining participants' models were expressed in such a way that they could not provide the basis for empirical tests. Their investigations were also characterized by relation-based reasoning, but without conceptual connections to elements of their initial models. Five of them (Emilla, Penny, Thad, Deanne, and Jerald) engaged in systematic testing of relationships between variables, but these variables were not included in their models or the models were stated as hypotheses without other conceptual relationships stated. Deanne's model, for example, simply stated that there would be an inverse relationship between the price of dinner at a restaurant and the amount of bacteria on the eating utensils. Five others (Buddy, Amber, Serena, Verna, and Sinda) did not have models stated in such a way that they could use them to systematically test relationships. Serena expressed her model as an experimental flowchart of testing for bacteria on one's hands after use of antibacterial soap, resulting in a simple descriptive system. She then proceeded to measure how many bacteria were on various surfaces after use of different types of soap. The inquiry questions of participants whose models did not provide a basis for their investigations seemed "plucked out of the air" without a reasoned basis for choosing particular experimental variables or designing the investigation.

Despite the disconnection between participants' models and their inquiries, almost all participants were capable of engaging in "school science" (i.e., a systematic study in which they identified variables, controlled conditions, and carefully collected data). Because of the way in which some of the participants framed their models, however, their investigations appeared at best poorly grounded and, in some instances, arbitrary.

Participants' Final Arguments: Method Directed Versus Theory Directed

In Table 2, we portray the relationships among the nature of participants' initial models, the aim of their inquiries, and the aim of their final arguments (we simplified the grouping of participants' "initial models" via the presence of theoretical mechanisms and the nature of conceptual relationships within the models). During final presentations, participants were required to provide arguments that linked their empirical evidence with conclusions about outcomes and with revisions made to their initial models. Our analysis here does not attempt to probe the rhetorical details of the arguments; rather, it attempts to characterize the aims of the arguments with regard to how investigative processes, empirical results, and theoretical relationships in the models were referenced in relation to one another. When this was used as a guide for analysis, two forms of argument emerged—method directed and theory directed—each having a distinctive object of critique, basis of argument, and point to the argument. *Method-directed argument* featured empirical conclusions such as covariance, significant differences, and changes over time as the object of the critique. The basis of the argument was how well the study was designed, how carefully and systematically the data were collected, and how accurate or appropriate the analysis was. The point of this form of argument was to convince others that empirically determined assertions about relationships between observable outcomes were valid. *Theory-directed argument,* in contrast, took as its object of critique a set of changes proposed to the underlying model based on the empirical findings. The basis of the arguments were the empirical conclusions (e.g., statements of significant differences, covariation). The point of theory-directed argument was to convince others that the possibility or character of unseen mechanisms was supported by evidence from observable outcomes.

Only two participants engaged in both method-directed and theory-directed argument (Jeanne and Colleen); they were able first to defend the validity of their investigative approach and second to create an argument that supported assertions about theoretical processes (Table 2, first entry in right-hand column). In Jeanne's case, she found supporting evidence for her hypothesis that various fabrics, on the basis of their molecular structure, would absorb different amounts of water, acidic, and basic solutions. When she presented her research to peers, she first used her experimental design, collection of data, and careful analysis to support her conclusions, characterizing the outcomes in terms of the experimental conditions (employing a method-directed argument). She then used her findings to support her hypothesis about unseen molecular-level interactions (employing a theory-directed argument). In Colleen's case, her theory-directed argument focused on disconfirming evidence that rye grass seedlings' energy expenditures through constant reorientations to gravity would result in less vigorous plants.

The remaining 19 participants employed only method-directed arguments (see Table 2, right-hand column). Two of them used their data to support a new system of descriptive relations between observable processes and used theory only in an ad hoc manner to reference their results. Five participants had included theoretical mechanisms in their initial models but did not or could not use the outcomes of their studies to reference these mechanisms. These participants spent their presentation time demonstrating relationships between observable variables or showing differences between comparison groups. Four of these participants (Carmen, Marla, Yvonne, and Gregor) nested theoretical processes in their models but did not test for any aspect of those hypothetical relationships and consequently could not then argue at the theoretical level. Two others not hypothesizing about unseen mechanisms were Cash and Phillip, who worked together on Newton's law of cooling. Their data were used to confirm what the model predicted. The initial models of the remaining 10 participants were constructed in such a way as to be unsuitable for providing a basis for empirical testing. Their data were similarly used to characterize the relationships between observable variables or differences between groups, but, because there were no underlying mechanisms hypothesized in the initial models, the data could not be used to refute or support aspects of the original models.

Of the 19 participants who engaged only in method-directed arguments about their investigations, 4 made minor changes to their initial models. Fifteen of the models remained unchanged because the data were used only to characterize empirical relationships. Most of the initial models did not include theoretical components; consequently, the investigations were not aimed at characterizing unseen mechanisms, and there was no basis upon which to revise the final models. Surprisingly, the course requirement that participants produce a "revised model" did not compel them to think beyond the empirical data in culminating their investigations and attempt to make such revisions.

Table 2

Nature of Participant-Generated Models and Their Integration Into Investigations, Grouped by Aims of Final Arguments

Participant	Nature of Initial Model	Aim of Inquiry in Relation to Initial Model	Aim of Final Arguments
		Model-based reasoning	
Colleen Jeanne	Theoretical mechanisms incorporated into model Represents relationships between observable, unobservable processes Example (Jeanne): how porosity, molecular structure, and surface area affect fabric absorbency	Tests for theoretical phenomena in model via observable relationships Example (Jeanne): how unseen mechanism—hydrophilic and hydrophobic fibers' reaction to liquids—influences absorbency	1. Theory directed—data used to support proposed theoretical relationships in model—*and* method directed—data used to characterize relationships between observable variables
		Relation-based reasoning	
Molly Lucille	No theoretical mechanisms in model Represents a relationship between two observable variables Example (Molly): involves sinking and floating, density, buoyancy	Tests for character of observable relationships identified in model Example (Molly): associations between density of liquid and buoyancy	2. Method directed: data used to support new system of descriptive relations between observable processes; theory is used ad hoc to speculate about outcomes
Carmen Marla Yvonne Gregor Michael	Theoretical mechanisms incorporated in model Represents relationships between observable, unobservable processes Example (Carmen): temperature influencing molecular interactions, oxygen's breakdown of vitamin C	Tests for character of observable relationships identified in model without reference to underlying mechanism Example (Carmen): temperature and vitamin C breakdown	3. Method directed: theoretical mechanisms in initial model, but argument does not address them

Phillip Cash	No theoretical mechanisms in model Represents change in one variable over time Example (Phillip): Newton's law of cooling, decay curve of temperature change over time	Tests for character of observable relationships identified in model and congruence with what model would predict Example (Phillip): model used as tool to predict how temperature changes under contrasting conditions	4. Method directed: data used to reason about, confirm what model predicts; no underlying mechanisms suggested in initial model, so unable to relate outcomes to theoretical causes
Emilla Penny Thad Deanne Jerald Buddy Amber Serena Verna Sinda	No theoretical mechanisms in model No conceptual relationships represented Example (Verna): flowchart of experimental procedure (how grapefruit extract kills bacteria; causal factors specified separately as "background information")	No conceptual connection to model Tests relationships between variables but variables not included in model Example (Verna): association between concentration of antibacterial agent and bacterial growth	5. Method directed: no underlying mechanisms suggested in initial model, so unable to relate outcomes to theoretical causes

Seeking Reasons for Participants' Difficulty in Practicing Model-Based Inquiry

In an attempt to make sense of the difficulty participants faced in the project, we found evidence that their histories with investigative science shaped their thinking about what a model is and what it means to do inquiry. We also found that, despite the carefully designed intervention, participants retained the belief that modeling and empirical inquiry were separate processes. Amber, for example, whose only investigative experiences were with highly structured lab exercises during her K–12 and college years, happened to record in her inquiry journal an annotated list of the phases of her inquiry. She included "researching the topic," but even though she was required to develop an initial model based on these readings, "creating a model" appeared nowhere on her list. Similarly, she included "drawing conclusions" as the final phase of her study but did not mention argument or revising the original model. Her investigative logic and the language she used to describe her work were constrained by the rhetoric of the scientific method. Although the literature confirms that learners at all levels have little experience with modeling and inquiry, we suspected that there was a more active explanation for participants' persistently conservative views of the processes of science and the critical role of models. We briefly outline here the influence of "backgrounds" on the thinking and practices of three additional individuals.

Yvonne came to the methods course with significant research experience from her precollege and college years. In middle school she had begun research on the effects of radiation on fruit flies, had won state and regional science fair competitions, and then had continued this line of research through high school. At the beginning of the course, Yvonne decided that her inquiry project would be an experiment similar to those she had done in middle and high school, but rather than using fruit flies as the objects of her radiation treatments, she used rye grass seeds. She planned to expose the seeds to varying amounts of microwave radiation and then test their growth rates after germination. Her initial model appeared to be informed by her previous work with fruit flies; she theorized about radiation damage to seedlings via thermal effects, vibration, mutation, and other factors. Her data collection involved testing for the character of known empirical relationships in her model (how amount of radiation related to seedling growth).

In presenting her final arguments to peers, Yvonne claimed that "microwave radiation was a mutagen and thus would harm seeds." In her argument to support this claim, she used experimental data to characterize the relationship between the conditions (varying amounts of radiation) and the outcomes (degree of seedling vigor). However, she did not use her empirical evidence to hypothesize about unseen mechanisms, and, not surprisingly, her initial model remained unchanged. She asserted in her journal that her model did not change because she "was not looking at molecular-level damage." Contrary to one of the fundamental precepts of investigative science, Yvonne did not believe that theoretical components of a model could or should be revised on the basis of observable phenomena.

In a further examination of Yvonne's journal, two connected themes became evident. One was that, for her, use of models was *not* a part of authentic inquiry, and the other was an unwavering adherence to the paradigm of investigative science she had grown accustomed to from her days in middle school. She wrote that the methods class project had only reinforced her ideas about how to "do science": "I relied on my old methodology to complete the inquiry." Yvonne maintained that she had used the scientific method for her previous studies but that, in this project, she was forced to use another approach—in her words, the "claim and model" method. She wrote: "I still feel the scientific method is the best way to approach inquiry for my students." In a final journal statement, she summarized how she viewed inquiry and the use of models as distinctly separate enterprises:

> From my personal experiences in laboratories I have found that scientists use the scientific method more than anything else. . . . Scientists in labs and in the field do use models, but they use them *only as tools to understand the phenomena they are studying* [italics added]. They communicate to other scientists by sharing models they have created based on their research results.

At the end of the course, when asked what still confused her about models, months of tension between her belief in the scientific method and our emphasis on models came to a head:

> The biggest thing for me with this model idea is—SO WHAT?!? I got really frustrated with having NO choice in whether or not to include models in my independent inquiry project. I think that my project using the regular "scientific method" was much easier to understand than having to have "beginning models" of my system and "revised models" of my system based on my research. I didn't test for any of the factors that I included in my model (which were molecular) so, what's the point of putting it in those terms?

Despite extensive research experiences, which had provided Yvonne with wide-ranging subject-matter knowledge and a useful repertoire of methodological strategies, she had compartmentalized the use of models as an activity disconnected from inquiry.

A second participant, Jeanne, had perhaps the most authentic investigative experiences before entering the teacher education program. In her senior year of undergraduate work, for example, she had been given a small budget and 5 days of work time aboard a research vessel to conduct oceanographic experiments. She had spent that time in the company of mentor scientists and other undergraduate researchers who were studying the role of microscopic sea life in underwater ecosystems.

She drew directly from these experiences to express how models were important to use in science teaching, not just as a convenient way to convey ideas about unobservable phenomena but to help students see how scientists move from data collection to mathematical models and understand the power of prediction with models:

> Once you have determined the system you want to observe, and have gathered data about it, you can develop a model. For example, an oceanographer wants to know the current primary production of phytoplankton at station P28 in South Sound. To do so, she measures chlorophyll concentration, temperature, salinity, and ambient light in the water column. . . . She creates a mathematical model to show the dependence of primary productivity on chlorophyll concentration and temperature. . . . To clarify, it is not always possible to fully observe the system that you're interested in. It is possible to create a model of that system, and to think in the context of that model when you are trying to determine how the actual system will respond to a change in one of its variables.

Her conception of a model was a system of directly measurable variables that could be used to predict events and processes not directly measurable. While this represents a sophisticated view, it also constrained her ideas about the kinds of phenomena that could be modeled. As an illustration, consider the following passage from a small-group conversation during class.

> *Jeanne:* I was thinking of areas where you couldn't use a model, and one of them was weather. It's a chaotic process. I thought maybe it's a good way to introduce—to have students think of what can and can't be modeled.
>
> *Second student:* Okay, I disagree that weather cannot be modeled—absolutely. You wouldn't say "model chemistry," you would model different processes in chemistry, and so for example you could really easily model convection but that wouldn't explain it all on its own, but you could model all the different factors that go into weather.
>
> *Jeanne:* But you couldn't predict what it's going to be like tomorrow with reasonable accuracy or 100% accuracy that a model affords you.

Here Jeanne reveals the limited perspective that probabilistic or conceptual representations cannot be considered models and that only phenomena that can be viewed in terms of deterministic formulas can be the subject of models.

In her inquiry project, Jeanne studied the absorption capacities of different types of fabrics (as described earlier). On the basis of her background readings, she hypothesized that certain types of materials would absorb more of an acidic solution than a neutral solution. The differential absorption of these solutions within the context of this investigation had not been confirmed in any science writing that Jeanne was familiar with; rather, it followed logically from her theoretical model. In her postcourse questionnaire, Jeanne was one of the few participants to state that modeling was (along with the scientific method) a part of doing science and "involved the pursuit of answers through research and testing." She noted that "models simulate systems that cannot be observed or tested directly" and repeated her language from the precourse questionnaire about models being composed of a set number of variables and serving to predict a "state of the system." This characterization of models seemed closely tied to her previous research experience in oceanographic systems wherein scientists use measurements of a number of observable underwater parameters to make predictions about theoretical processes (e.g., how temperature stimulates the growth of underwater plant life) that are virtually impossible to measure directly.

Jeanne seemed to have conceptually integrated the use of models with scientific investigation. When asked what was still confusing about models, however, Jeanne claimed, as did Yvonne, that there was some type of methodological separation between the use of models and the scientific method. She wrote:

> I just believe that there are certain circumstances where models are useful, such as in understanding abstract or nonvisible events, and other circumstances where the scientific method is useful. I think the scientific method is key in generating certain aspects of models like identification of variables, putting limits on variables, and identifying causal relationships.

So, despite the sophisticated coordination of models and inquiry in her own project, Jeanne subscribed to the idea that it is possible to use the scientific method to lay the groundwork for creating models without having the empirical investigation generated explicitly or implicitly from an existing model of how the world works.

A third participant, Sinda, had extensive knowledge about the earth sciences but little research experience in her background. She recalled only one investigation she had done in high school: observing the feeding behaviors of box turtles. During an undergraduate internship, she had shadowed a fisheries biologist and assisted him in data collection but had not designed studies or been involved in making sense of the findings. We noted that Sinda was the only participant to mention models performing under "ideal conditions." She believed that the difference between a model and the real thing was that "models have some sort of control. . . . They are applied under ideal conditions that may contradict what happens in the real world."

Sinda began her own project as an enthusiastic novice; she was interested in soil additives (e.g., perlite, sphagnum moss) and in comparing how much water each of them could absorb. Her initial model consisted of a set of four statements; she referred to these statements as her "initial theories," although there were no apparent conceptual links among the statements. Her "theories" were

> that spongier materials such as cedar chips will have a better water holding capacity; that lava rock will absorb more water than gravel

> because it is more porous; that vermiculite and sand will absorb the most water because they have finer particles which increase the surface tension of water; and that Moisture Soil will have higher water holding capacity than subsoil because it has more fibrous material in it.

Sinda read extensively on the water holding capacity of these materials and had mentioned capillary action (in her journal) as a possible mechanism, but she did not explore this idea in her investigation or in developing her model. Her investigation was a comparative water retention test on a variety of soil additives; however, the design of the study did not allow retention results to be associated with any consistent independent variable. When she presented her study and final conclusions to peers, her key claim was that "fine-grained materials with more tightly packed particles have the highest water holding capacity." She used a method-directed argument to support this statement but then was unable to relate these observable outcomes to underlying causes. She showed, as her final model, a bar graph indicating the amount of water retained by each of the soil additives.

We puzzled over how Sinda could have chosen a bar graph to represent a final model. A possible answer appeared in her journal. There she suggested that the "model" for her study was not based on the abstract phenomenon of absorption but, rather, on that of a rainstorm:

> I felt my inquiry was a representation of the phenomenon I was researching and trying to explain. The eye-opener came when I was conducting the experiment and realized I could not replicate a real rainstorm. Dumping water on top was more similar to a flood or mudslide and may have pushed water through the medium.

Sinda had apparently used her earth science background to conceptualize what a model was supposed to be. In the earth sciences, many phenomena are generated in scaled "mock-up" settings that simulate inaccessible or extreme conditions in the interior of the earth, in the atmosphere, or on other planets. The use of mock-ups or working physical models (such as for watersheds or volcanoes) is the only way, in many cases, to conduct controlled experiments. This is what Sinda may have been cautioning about earlier concerning models being used under "ideal conditions." She had also written in her journal about testing in the earth sciences:

> A good example is our knowledge of the layers of the earth and the formation of rocks. We can't travel down into the earth and see these processes happening. Yet we can create similar conditions in a lab to study and theorize how things happen (such as melting rocks at extremely high temperatures and cooling them to study crystal formation). Much of science is done this way because we are limited in our ability to witness such things as the formation of mid-ocean ridges and movement of crustal plates.

At the end of the course, Sinda reflected on her inquiry experiences, claiming that she "was less than a novice at completing full inquiries" and that she "had always been given the question to start with." She recalled that her previous studies had never included assumptions, predictions, argumentation, or initial theories; none required supporting one's claims, presenting to peers, or looking up other studies. She said she had now changed her mental model of inquiry that previously she had "considered as step by step, very orderly."

In the case of these three participants and most others, there was ample evidence that their conceptualizations of model-grounded inquiry were influenced in no small part by past investigative experiences and, in particular, by the architecture of the scientific method.

Postcourse Changes in Participants' Understandings of Models

Three months after participants' final presentations, a postcourse questionnaire and entries from participants' journals were used to assess changes in their understanding of models. Of the 14 participants who had scored less than the maximum in the precourse questionnaire, 11 had made advances by the end of the second-quarter course in understanding the nature or function of models, or both. Of the 7 who had originally been rated high (scoring the maximum), 3 had decreased a level in either nature or function categories, and the others had remained at the same level (Table 3). Using data from additional sources, we found evidence that these lower scores were due to a lack of thoroughness in responding to the questionnaire as opposed to regression in understanding.

The primary way most participants grew in their knowledge of models was their realization that processes as well as objects could be modeled or that models could take on broader forms of representation (i.e., diagrams, mathematical equations, verbal explanations, etc.). Eight participants made advances in this area. For example, in her precourse questionnaire, Emilla had given examples of models as replicas or three-dimensional plastic figures and had said that the most important aspect of developing a model is to "be accurate." In her postcourse questionnaire, she explained that a model is "anything that helps us understand ideas." Models are "ways to gather your ideas or see where your theories have flaws."

In contrast to the easy acceptance of processes as models, the most resistant understanding among some participants was that models are always representations of "real" entities or processes whose existence has simply to be empirically confirmed by scientists. Only a few participants stated unambiguously that a model is a human construct that helps us understand a world in which reality cannot be isomorphically mapped onto such models. The ontological status of models from these two perspectives is different, with implications not only for how models are thought about but for how one might teach about them. Logic suggests that if teachers believe a model is an unproblematic representation of a real-world structure or process, they are less likely to value its development by students or value helping students

Table 3

Case-Ordered Display of Participants' Changes in Course Ratings on "Understanding of Models" Arranged From Higher to Lower Postcourse Ratings

	Understanding of Models			Teaching About Models	
Participant	Postcourse: Nature of Models (Change from Precourse; Range: 1–3)	Postcourse: Function of Models (Change from Precourse; Range: 1–3)	Net Composite Precourse-Postcourse Gain/Loss	Precourse[a]	Postcourse[b]
Colleen	3 (no change)	3 (no change)	No change	M	T
Jeanne	3 (no change)	3 (no change)	No change	M	T
Cash	3 (no change)	3 (no change)	No change	M	T
Deanne	3 (no change)	3 (no change)	No change		
Verna	3 (+1)	3 (no change)	+1		T
Buddy	2 (−1)	3 (no change)	−1	M	T
Michael	2 (−1)	3 (no change)	−1		T
Molly	3 (no change)	2 (−1)	−1	M	T
Thad	2 (no change)	3 (no change)	No change	M	
Phillip	2 (no change)	3 (+1)	+1		
Marla	2 (no change)	3 (+1)	+1		
Sinda	3 (+1)	2 (no change)	+1		T
Jerald	2 (+1)	3 (+1)	+2		
Emilla	2 (+1)	3 (+2)	+3		T
Gregor	2 (+1)	3 (+2)	+3		
Lucille	2 (+1)	2 (no change)	+1		
Serena	2 (+1)	2 (no change)	+1		
Amber	2 (no change)	1 (−1)	−1		
Yvonne	2 (no change)	1 (no change)	No change		T
Penny	1 (no change)	2 (+1)	+1		
Carmen	2 (+1)	1 (no change)	+1		T

[a]Participants indicating on precourse questionnaire that teaching the idea of models and modeling was important (M).
[b]Participants incorporating the idea of modeling into their student teaching practicum unit plans (T).

understand the nature and function of models. Those participants who recognized models as objects of conjecture and critique were indeed more likely to incorporate models in these roles into their plans for teaching, as the following paragraphs describe.

During the second quarter of the methods course, students developed an inquiry-based unit of instruction that they used in their own classrooms the following fall. Participants were not prompted to incorporate the idea of models into their units. In the postcourse questionnaire, participants were asked to describe these units and, in particular, what their students would be doing during the units. In their responses and in the units themselves, we looked for examples of using models to exemplify the nature of science and the role of models in inquiry. Three examples were as follows: (a) Colleen's plans to have her students develop a model of a hearing organism and refine that model throughout the unit as they learned more about the physics of sound, (b) Molly's plans to have her students develop a model of the relationship between pressure and volume in a gas and then use experiments and argumentation to support their theories, and (c) Buddy's plans for his students to hypothesize about models for plate tectonics as they learned about different bodies of evidence for that process and then change their models as they "recognized fits and contradictions" in the evidence. While not all of these planned activities reflect the most rigorous forms of model-based reasoning, they do represent pedagogical intentions to teach about key scientific ideas as models, to demonstrate that models are purposefully constructed, and to involve students in revising models on the basis of new evidence.

In total, 11 of the 21 participants mentioned using models in these ways in the classroom (Table 3, see "T" entries). Five of these 11 participants were among the 6 who had suggested on the precourse questionnaire that it was important to teach about the role of models in science (see "M" entries in Table 3). Of the 6 others who were planning to use models in their units to teach about the nature of science and inquiry, 4 had made gains in the understanding of models from the precourse to the postcourse questionnaire. It should be noted here that no one in any of the previous cohorts of preservice teachers (before this emphasis on models was integrated into course activities) had made mention of topics as scientific models in the units they prepared for student teaching.

Discussion

The findings can be grouped under three broad statements. First, an instructional focus on models in science, grounded in extended PDE episodes, can advance the thinking of most preservice teachers about the nature and function of models. Second, even though preservice teachers are able to talk about the idea of models in sophisticated ways given contextualized examples, they are almost wholly unfamiliar with generating theoretical models to ground empirical investigations or employing model-based reasoning to make sense of their findings. Third, elements of individuals' previous experiences with research and with the "scientific method" can result in durable conceptual frameworks that, in many cases, subvert more sophisticated understandings of models and their roles in empirical investigations. The following sections elaborate on these assertions.

Changes in the Way Preservice Teachers Think About Models

The initial conceptions of models held by participants were consistent with those of beginning and experienced science teachers in similar studies (Crawford & Cullin, 2004; DeJong & Van Driel, 2001; Harrison, 2001; Smit & Finegold, 1995). Even after extensive undergraduate coursework in science, only a third of participants demonstrated a sophisticated understanding of both the nature and function of models. Most believed that models were representations of "real" processes, and several spoke of models only as representing tangible objects. Two thirds of the participants thought the purpose of scientific models was simply to illustrate ideas, to help one think more clearly about an idea or teach someone else about it. As in other studies, few were able to talk about models as tools for theory building or the conceptual grounding for investigations. Apparently, undergraduate experiences do little to advance the idea of models beyond that of acting as pedagogical props.

Instructional activities over the two quarters appeared to have significant but targeted effects on participants' conceptions of models. Eleven of the 14 participants who did not already have an expert understanding advanced their ideas about the nature of models, the function of models, or both. Certain aspects of modeling seemed easy for participants to incorporate into their systems of understanding. Most who originally believed that models were representations only of "entities" such as the interior of a cell had little difficulty later talking about models of processes when engaged in conversations around the micro-teaching and technology activities. For many participants, it was not difficult to begin thinking in terms of models as predictive tools. Some had major revelations about models, and these conceptual shifts were often traceable to specific elements of instruction. An entry in Sinda's journal, for example, connects a key insight of hers to the paper we provided about scientific models:

> Before we were given the handout on models and inquiry, I do not think I had a good idea of what a model was. I knew things like Newton's laws, natural selection, and plate tectonics were models, but I did not fully understand how to separate that from phenomena. Further, I did not realize that there were different types of models. I had used many of the models but had not realized it. *I know now, however, that models are not the phenomena, but a way to explain them and can take the form of representations as well as ideas and processes* [italics added].

She and others also commented on learning about a *variety* of models and coming to understand how they represent ideas and processes. This may be attributable to their involvement over time with multiple forms of models during the micro-teaching, the technology simulations, and the inquiry projects themselves.

What was difficult to change was participants' beliefs that models represent an objective reality. This presented a dilemma in analyzing their understandings of models. Most participants referred to models being imperfect representations of the "real thing." It would be logical to assume that this indicated a belief in objective reality. From the context of their responses, however, it seemed that the "real thing" referred not to an objective reality but to humans' experiences of reality. This ontological dilemma notwithstanding, among participants who indicated a belief in an objective truth when explaining natural phenomena, the instruction over two quarters did little to change this belief.

A second successful dimension of the study was the number of participants who planned to incorporate the idea of models into their teaching practice. All participants had initially agreed in the precourse questionnaire and in early informal interviews that it was valuable to teach *with* models. For most, this meant only using models, such as those for atomic structure or the nitrogen cycle, to communicate abstract or complex ideas to learners. A few individuals, however (six of the top nine precourse scorers), believed that it was also important to teach *about* models as tentative human constructions and intellectual objects of critique. Some of these individuals ultimately felt it was important for students to create their own models to learn these lessons. Thus, it appears that individuals who recognize models only as simplified representations of an objective reality do not consider *the idea of modeling* as a valuable goal of science learning. Conversely, individuals with sophisticated conceptions of modeling are more likely to integrate these ideas into pedagogical plans for acquainting students with how scientific knowledge is constructed and advanced. At the end of the course, more than half of the participants (11 of 21) had, without prompting from the instructor, included modeling strategies in unit plans for their upcoming teaching practicums (we restrict our claims here to "planning" because we did not observe the actual student teaching).

These results contrast with those of the Crawford and Cullin (2004) intervention that helped participants advance the way they conceptualized and talked about models but had little effect on their intentions to teach about models. We believe that two aspects of our instructional approach were effective in getting teachers to consider using models in their own teaching. The first was involving participants, as learners, in teaching sequences in which models were collaboratively developed. The pulley investigation during the first micro-teaching session, for example, allowed them an "entry point" into the discourse of models and involved them early in conversations that linked models with classroom inquiry. The second effective feature was the repeated integration of model discourse throughout the first 3 months. Participants engaged in multiple conversations in varying instructional contexts about the relationships between models and evidence—they eventually adopted the classroom norm of referring to scientific concepts as conjectural representations.

While it is likely that the combination of course resources and activities influenced participants' thinking, some resources seemed more valuable than others. For several participants, the paper we wrote and distributed (giving a comprehensive description of scientific models, explaining the relationship between models and other forms of scientific knowledge, and positioning the testing of models as the central activity of science) appeared to be the most valuable intellectual resource. As the earlier quotation from Sinda suggests, the explicit and comprehensive nature of that text stimulated fundamental conceptual change about models among some students. In contrast, the inquiry journal, while helpful to the researchers in revealing the thinking of participants, seemed to serve primarily a reporting rather than a reflective function and did not appear to be useful in contributing to changes in participants' thinking about models and investigations.

Participants' Difficulty in Creating and Testing Their Own Models

Although the course experiences advanced the thinking of many participants, it is difficult to assess the specific impact of the inquiry project, given that so many of our students could not create suitable models to ground their investigations. In developing their models, some constructed experimental flowcharts rather than representations of the theoretical system they were investigating. Others presented a list of statements that all referred to a common phenomenon but were not conceptually integrated with each other, and some framed their models simply as experimental hypotheses.

If one does not identify a model with some hypothesized process to test for, it is virtually impossible to then use model-based reasoning to argue for revisions of that model. Because only two participants (Jeanne and Colleen) both represented unobservable mechanisms in their model and tested for their effects, they were the only ones who could engage in a theory-directed argument about what the observable outcomes suggested of underlying theoretical processes. The remainder of the participants employed only method-directed arguments, using relation-based reasoning to link their outcomes to experimental conditions. In the case of more than half of these individuals, it was impossible to use their data as evidence to refute theoretical aspects of their models because their initial models did not reflect the phenomena they were studying, were stated in such a way as to make appropriate testing impossible, or did not posit underlying mechanisms.

Some participants, while planning for their inquiry, could not recognize aspects of their own conceptual frameworks as relevant parts of testable models. Many, who had sparse or simple descriptive models, had written additional relevant information about the central phenomena into their journals or final presentations but labeled it separately from the model as "background information." These ideas could readily have been integrated into the stated models to create richer networks that involved theoretical mechanisms.

These difficulties seemed contradictory to the ease with which participants spoke of models *presented to them* during instruction. In the technology assignment, for example, even those participants whose ideas of models were least congruent or complete with regard to the scientific perspective were easily able to identify conceptual models within computer-based simulations, to describe how these models could predict phenomena in a variety of contexts, and to point out limitations in the model that would compromise the theory-data fit under certain real conditions. These results suggest that we may have to reevaluate our conception of what it means to have an "expert-level understanding" of models. Much of how we currently assess this understanding is by asking individuals to speak about features of models in the abstract, talk about provided examples of models, or name examples of models. But using only these techniques may be analogous to interviewing literary critics who can skillfully analyze the writing of others without being able to produce a praiseworthy novel themselves. Detecting another level of mastery should involve participants constructing their own models given a context, content resources, and a purpose. Only in this way can we be sure that participants' understanding transcends "knowledge in the abstract," and it is the only type of performance that suggests whether they will be able to mentor their own students through such a process.

We did not anticipate that creating models would pose such an obstacle to participants. We now appreciate, however, that this challenge involves the coordination of intellectual tasks rarely practiced in science education at any level. Initially, one needs to identify a particular conceptual process or entity as the focus of the model (i.e., "What are we creating a model *of*?"). One must then consider the purpose of the model and how this influences the way a system of associations among objects, properties, and events (some empirical and some theoretical) is to be represented. Then, in all but the simplest self-contained natural systems, one must decide what the boundaries are for the model and what is *not* going to be included. To add to the "messiness" of talking about models and their link with inquiry, one has to address the issue of causality. What "counts" as a causal mechanism? Many junior high school students know that the shorter the string on a pendulum, the faster it swings, but could the length of string be considered causal? Even the simplest observable phenomena are often controlled by underlying mechanisms that are complex, contingent, and interactive (see Perkins & Grotzer, 2000, or Hestenes, 1995). Admittedly, if we want young learners to investigate models in scientifically authentic ways, we will have to strategically scaffold the tasks just mentioned and most likely identify a number of models suitable for study at different grade levels that include comprehensible causal underpinnings (see Jackson, Stratford, Krajcik, & Soloway, 1995, or Schwarz & White, 2005).

Influence of Past Investigative Experiences on Conceptions of Models and Inquiry

When degree of previous research experience was cross referenced against participants' initial understandings of models, it appeared that there was no relationship. Approximately half of the participants with significant research experience were not able to describe the nature and function of models in the most sophisticated terms, while several participants with little or no research experience provided evidence of a deep understanding of models. Apparently even extensive precollege and undergraduate “lab work” does not always furnish the background experiences necessary to cultivate expert discourse around models and modeling. Rather, these conceptions are shaped by specific types of investigative experiences as well as the way models are referenced during those experiences.

For Yvonne, the idea of a scientific model was relatively unfamiliar and not connected to inquiry. She came to see the required use of models in class as an imposition, even a threat to her closely held views of the scientific method as the standard protocol for inquiry. Her long history of science fair competitions reinforced in her an intractable set of beliefs about what the focus and outcomes of investigations should be, and for her observable outcomes could not be used to theorize about the unseen. This incommensurability was evident in the label she created for the activities in the class inquiry project—the “models and claims” method. For Yvonne, models within the context of inquiry were relegated to the status of hypotheses or “works in progress.”

For Jeanne, the idea of a model was drawn from her oceanography experience. This schema included the following: the necessity of identifying key variables, models as “dynamic systems,” the mathematizing of models with the goal of calculating values for variables that cannot be measured directly, and seeking more powerful models that can predict under a variety of circumstances. These are all characteristic of how many oceanographic biologists conceptualize models in their domain. She was one of only two participants who attempted to uncover evidence of processes that were not directly observable. The idea of modeling to her was integrated with her ideas about inquiry, and thus, as a contrast to Yvonne, there was compatibility rather than tension between the two agendas.

Sinda’s extensive background in earth science similarly shaped her thinking. Even though she understood a variety of examples of models, the kind of model she believed was necessary for an empirical inquiry was a physical mock-up emulating conditions that were not directly observable or controllable. This concrete image of models came from her experience with labs that simulated, among other things, pressure and temperature in the interior of the earth. Sinda apparently felt she had to incorporate such a model into her inquiry. Her “rainfall” model, however, was not a conceptual centerpiece of data collection, nor could it have been an object of critique and revision; thus, Sinda was left with a bar graph for her final model and some confusion over how models could be advanced through investigations.

For all participants, the idea of the “scientific method” was the fundamental organizing theme. Yvonne viewed it as an unassailable paradigm guiding activity and reasoning. Jeanne, too, saw it as an enterprise separate from the use of models, although for her model building was complementary to inquiry, not a replacement for it. From her perspective, scientists first collect data (apparently with no theory or model guiding them) and, when enough data have been collected, they then develop a model. Amber summarized her inquiry project experience in her journal by re-creating the procedural steps of her investigation—a framework tied to the familiar script of the scientific method. These examples illustrate that the scientific method, as an artifact of the school science culture, provides an initial way to guide classroom activity but that its oversimplified approach actively subverts more authentic and model-grounded ways of thinking about inquiry.

Within the norms of "school science," all of the participants completed what could be considered perfectly acceptable inquiries. For example, even though a number of them did not base their investigations on models in any substantive way, they posed testable questions, designed appropriate data collection strategies, methodically collected data, and crafted (method-directed) conclusions that were justified in light of the evidence. In most science classrooms, this would constitute "doing science" in spite of the fact that such inquiries do not serve the prime function of science: to refine explanatory models of the way the world works.

In critiquing the traditional scientific method, we do not mean to imply its effects are entirely negative. Even though it encourages naive empiricism and often dispenses with the need for deep content knowledge to inform the inquiry process, it provides the only structure within which many teachers feel comfortable engaging their students in hands-on work. Teachers relying on this heuristic are often very successful in getting their students to ask inquiry-appropriate questions, to work with the materials of science, and to talk about data. We do advocate, however, that models become central features of school science investigations. For most learners, this would require a "guided" version of model-based inquiry, with teachers heavily scaffolding the development of models using students' ideas and content resources. The crafting of model-grounded questions would also have to be facilitated by teachers, and, perhaps most important, the teacher would have to demonstrate how to use empirical data to argue about the theoretical components of models.

Revising the Intervention Framework

Clearly, not all aspects of the course design were effective. In hindsight, the instructional approach of the methods course ignored several dimensions of understanding that appear to distinguish mere knowledge of models from the ability to integrate models and model-based reasoning into inquiry. These dimensions are as follows: (a) recognizing the theoretical underpinnings of models that depict observable phenomena, (b) creating and identifying models in forms suitable for empirical testing, (c) understanding how to craft testable questions based on a model, and (d) generating arguments in which empirical evidence is used to support or refute theoretical aspects of the model. Leaving these dimensions unaddressed probably contributed to participants maintaining their belief that modeling and inquiry are conceptually exclusive enterprises.

Reflecting upon these outcomes, we now consider PDE (Engle & Conant, 2002) to be more a set of broad principles than a model for developing long-term experiences aimed at complex understandings and conceptual change. We still see PDE as a "top-level" organizer for thinking about instruction, but we consider a set of "middle-level" guidelines necessary to compose an instructional model that can be used specifically to help preservice teachers develop their understandings of science. Drawing on our findings, we have developed a framework for designing model-based inquiry experiences (Figure 2). The logic underlying this framework is based on two ideas that were brought out in full relief by this study. The first of these ideas is a "complexity" issue—that model-based inquiry is methodologically and epistemologically more sophisticated than common forms of school science investigations. The second is a "credibility" issue—that folk theory about an unproblematic scientific method is so deeply rooted in school science culture and in the minds of learners that it actively competes with model-based inquiry as an acceptable, authoritative representation of how science is done.

There are five features of this model that address the complexity and credibility issues associated with model-based inquiry. The first feature is engaging students early in a whole-class, teacher-guided inquiry that shows how all of the "pieces" of a model-grounded investigation fit together: demonstrating how one creates a conceptual model, crafts a question based on that model, collects data, and uses theory-directed as well as method-directed argument to connect evidence with the original model. The second is creating material resources that illuminate the predominant forms of knowledge in science (theory, law, model, hypothesis) and the roles they play in inquiry. These resources should specifically explain the nature of theoretical versus empirical aspects of models and should be introduced early in the course. We had assumed that in asking our participants (who all held degrees in science) to develop a model and "test some aspect of it," most would be able to include, test for, and argue for underlying causal associations. We now recognize that these skills must be explicitly addressed by the instructor and that the language of "theory" must be practiced (by participants) in multiple contexts if it is to become meaningfully internalized.

The third feature is creating a sense of dissatisfaction with the idea that science inquiry begins with theory-free observation and culminates with validation of statistical findings. We would present historical cases of scientific research programs that made transparent their initial working models and used empirical findings to suggest changes in these models. Accounts of the discovery of DNA's structure or the development of the theory of plate tectonics might make compelling examples. Fourth, participants would be required to engage in an independent inquiry project, as they were in this study. However, they would be specifically required to incorporate features of authentic science that are not typically addressed in school science (e.g., developing a tentative model at the outset that includes hypothesized processes or entities and generating final arguments in which empirical evidence is used to support or refute claims about theoretical mechanisms).

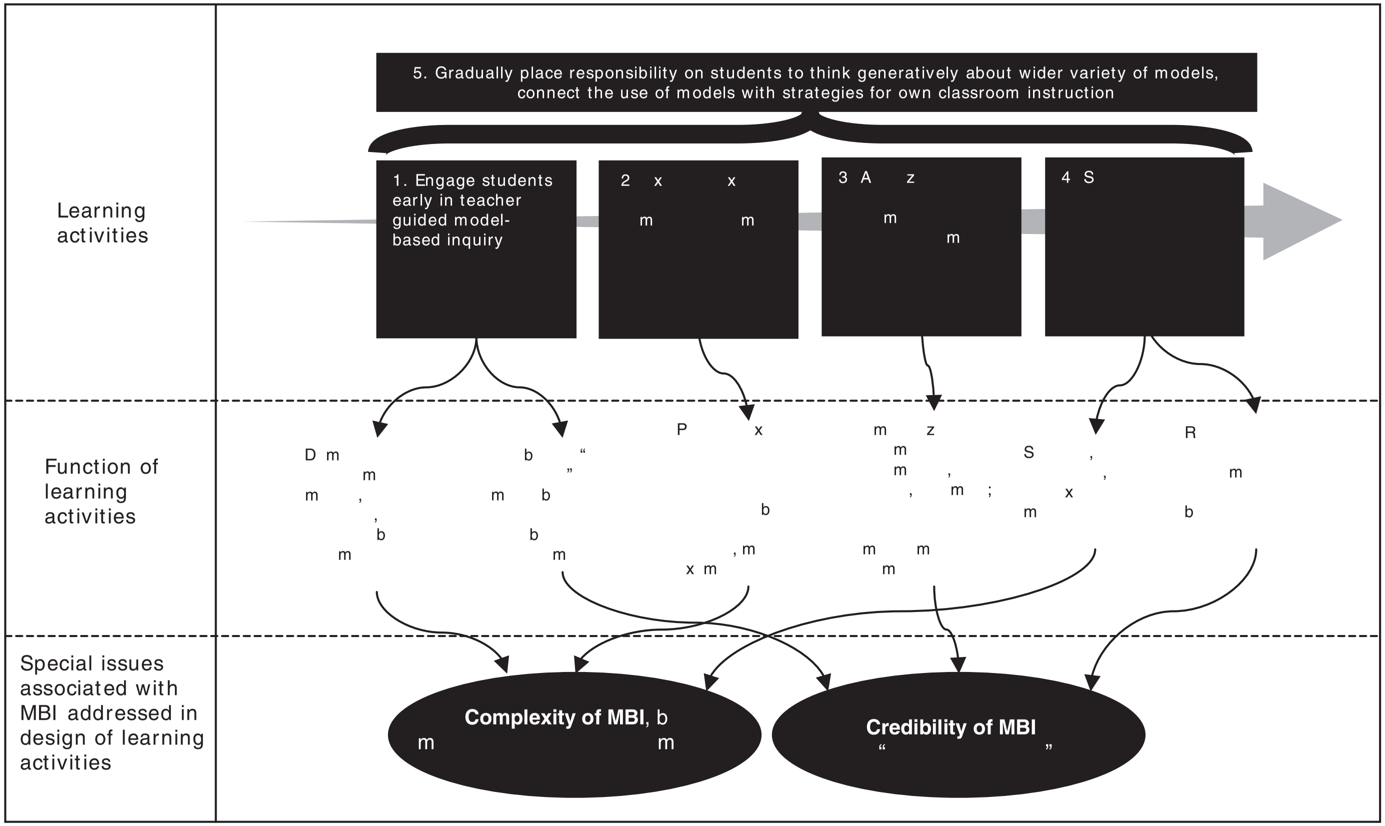

Figure 2. **Framework for designing model-based inquiry experiences.**

Feedback from instructors would play a much larger role in these inquiry projects. As participants are developing their own inquiries, instructors would “check in” early in the process and offer critical comments on their developing models, their investigative questions, and the claims they intend to present in class. And fifth, we advocate that, over time, activities gradually place more responsibility on the participants to think generatively about a wider variety of models and to connect the use of models with strategies for their own classroom instruction.

This five-part framework was recently used in a new study with 18 secondary preservice teachers. Preliminary results indicate that participants’ final levels of understanding and practice of science significantly exceeded those of participants in the study described here. In addition, this follow-up study strongly suggests that the framework works best when implemented as a system of mutually reinforcing experiences rather than a smorgasbord of individual activities from which an instructor might choose. Given these results, we see no reason why the model-based inquiry framework cannot be successfully used with undergraduate or even secondary school learners.

Conclusions

As mentioned earlier, given the current emphasis on students’ understanding of authentic scientific activity, it is important to recognize teachers’ competencies with modeling and inquiry as crucial elements of pedagogical content knowledge. This study provides evidence that an extended instructional focus on scientific models can foster more sophisticated thinking about this key disciplinary genre of representation.

While some of the findings are encouraging, the efforts to help these preservice teachers link models with inquiry in a way similar to that advocated in the reform literature for young learners were only partially successful. These efforts revealed that past experiences, including both undergraduate investigative experiences and repeated exposure to the “scientific method,” constrained participants’ understandings of doing science. The following findings provide a baseline from which more targeted research and interventions in these areas can be designed.

1. Instruction grounded in productive disciplinary engagement can advance preservice teachers’ understandings of scientific models and positively influence their plans for using modeling activities with their own students.
2. Expert understanding of the nature and function of models is closely tied to the belief that it is important to teach about models as intellectual objects of critique and revision.
3. Using theoretical models as the basis for empirical investigations requires specific intellectual resources and reasoning strategies that are significantly more advanced than a generic understanding of scientific models.

4. Past investigative experiences contribute to durable conceptual frameworks for what is recognized as a model and the ways models can be incorporated into inquiry.
5. For most preservice teachers, the "scientific method" remains the dominant procedural framework for thinking about inquiry—to the exclusion of considering theoretical models as the basis for fruitful questions and for conceptual refinements after investigations.

At the outset of this article, we suggested that entire lines of epistemic discourse are missing from school science. Our participants' tenuous grasp of the rhetoric of modeling supports this assertion. Despite our personal enthusiasm for teaching about the role of models and theory in the methods course, we do not feel that teacher preparation programs should be the first environments in which future educators engage in substantive conversations about the nature of science. Models are the primary mediational tools employed by science to bridge the realm of ideas with the world of material experience. As such, they should figure prominently in the curriculum at all levels of education rather than occupy the periphery of instructional agendas.

Importantly, our findings were derived from individuals who are the products of a typical science "upbringing" through the U.S. K–16 educational system: preprofessionals who are poised to enter our classrooms, mentor our children through inquiry experiences, and, it is hoped, break with traditionally conservative ways of portraying science to children. This research casts new light on how teachers think about the work of science, but the picture, of course, remains far from complete.

APPENDIX A

Technology Assignment

1. Select one simulation from today, identify one model, and state it in generalized form (usually as a rule or set of connected rules). Use additional details if necessary to describe the model other than the rule(s).
2. Are there any factors that may influence the relationships in your model that you know about but cannot express well in your model statement?
3. State two circumstances in which this model would be helpful in predicting some natural phenomena.
4. Describe one circumstance where, because of unusual factors present, your model would not be sufficient to predict some natural phenomena. Give details about why it would not be predictive.
5. To familiarize students with the objects, events, and relationships in this simulation, what simple structured task could you ask students to do in the simulation?
6. After this initial structured task, what key ideas/concepts would you then introduce into a class discussion to help them further explore the model?

7. What advanced task might you eventually ask high-level students to do with the simulation in order to challenge them? (Quantifying models by taking data in the simulation is one possible way; there are others.)

APPENDIX B

Postcourse Questionnaire

Background questions on your opportunities to "do science":

1. In your science education experience from middle school through undergraduate years, have you ever been given the chance to design and carry out your own investigation? If yes, can you say approximately how often and give the most memorable example?
2. Have you ever had the opportunity to "do science" outside of a school setting, worked in a laboratory, or done field work with scientists? If so, can you describe these opportunities and describe if you participated in developing the research questions, designing how to collect data, and engaging in discussions about the research. Was your role restricted to data collection?
3. What do you think are the central features of what it means to "do science" in classrooms? What kinds of understandings or skills do you think kids can get out of doing science?
4. Please describe the inquiry in your unit plan and describe what your students will be doing during that inquiry. How is what your students will be doing a part of inquiry?

Questions regarding scientific models:

5. If you had to describe what scientific models are to fellow teacher education students, what would you tell them?
6. In your opinion, what are models in science used for (not in science education, but in science)? If you can think of multiple ways, please state them all.
7. What is still confusing to you about the idea of models in science?
8. Are there any examples of models in the unit you are developing? If so, what are the important ones?

Notes

This study extends a line of research that seeks to develop evidence-based innovations in preservice education by tracking shifts in pedagogical reasoning and instructional practices of novice educators over time. Current studies in this program of research are also examining the broader trajectory of science teacher development, from undergraduate work through preservice programs and into the early years of professional service. The ultimate aim is to develop educators who are both grounded in their discipline and capable of adapting instruction to the needs of diverse learners.

[1]The terms "theory" and "model" are often used interchangeably in both educational research and school science. Philosophers of science, however, consider theories to be a

"family of structures (models) that serve to explain phenomena in a field of inquiry" (Van Frassen, 1980, p. 64). The theory of evolution, for example is made up of many related models. One of these is a model for heritability (how traits are passed from parent to offspring); another is superfecundity (the idea that some species produce many more offspring than can possibly survive); another is the idea of random mutations occurring in a population; and yet another is the idea that populations rather than individuals adapt to their environments over time. Theories such as evolution or plate tectonics are judged on whether their constituent models fit the world (Giere, 1991). Given these distinctions, we use the term "models" or "theoretical models" rather than "theories" to describe the objects of intellectual focus during the methods course and the conceptual entities that served to ground participants' investigations.

[2]Another example involves 19th-century natural historian Louis Agassiz, who publicly preached inductivism and held that "a fact is as sacred as a moral principle" (1874, p. 95). Historians note, however, that he used polygenist theories to shape his data collection on the physical features of non-White races (see Menand, 2001).

[3]We used slightly different wording from the precourse instrument because we did not want participants to simply restate responses they had used in the previous questionnaire. The postcourse questions, however, did tap into the same fundamental concepts as the precourse questionnaire: the nature of models, the function of models, and a range of examples of models. The postcourse questions were fewer and were stated more broadly than in the precourse instrument, which may have in fact underestimated participants' conceptual progress.

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