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MoDeLS: Designing Supports for Teachers Using Scientific Modeling

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Abstract

Scientific modeling is a crucial scientific practice, yet it is rarely incorporated into elementary and middle school classrooms. Teachers typically have limited knowledge of models and modeling or of students' ideas about models and modeling. Yet engaging in scientific modeling in the classroom places a high demand on teachers, and they typically do not have access to high-quality modeling-oriented curriculum materials. The MoDeLS project works to design innovative and effective supports for teachers' learning around scientific models and modeling. These teacher learning opportunities are incorporated into educative curriculum materials and teacher education experiences. The design of these opportunities is guided by teacher learning goals associated with a teacher knowledge framework that focuses on teachers' epistemological metamodeling knowledge of models and modeling practices as well as their pedagogical content knowledge for scientific modeling. The paper discusses the learning goal driven approach used and describes some of the supports for teacher learning incorporated into both educative curriculum materials and teacher education experiences. The paper also discusses the design challenges inherent in this type of work, and closes with a discussion of implications for curriculum developers, science teacher educators, and science education researchers.

Introduction

Consider the typical elementary science experience of building a volcano model using baking soda and vinegar. Is this really a scientific model? What scientific practices will children gain through the construction of such a model? What higher-level knowledge will they develop about how science is conducted? What science content will they learn? And, how can a teacher differentiate between scientific models and exciting activities? In the MoDeLS (Modeling Designs for Learning Science) project, we explore questions like these. In this paper, we describe our approach to designing learning opportunities for teachers interested in using models and modeling in their classrooms.

Scientific Modeling in Schools

A scientific model is an abstraction and simplification of a system that make its central features explicit and visible, allowing someone—a scientist, a teacher, or a learner—to illustrate, generate explanations, or make predictions of natural phenomena (Harrison & Treagust, 2000). In this sense, then, the volcano described above cannot easily be used as a scientific model, since it does not accurately explain the phenomenon of volcanic activity. The term *model* in science learning is typically used in two related ways (Gobert & Buckley, 2000). First, a conceptual or mental model refers to the individual's internal representation, or their understanding of a phenomenon. With teachers and students, we refer to this as the "idea model." Second, expressed models are external representations of an individual's idea model, and may be simply verbal descriptions, or more typically are inscriptions such diagrams, material depictions, or computer simulations. Such idea models and expressed models are the product of scientific modeling.

Current reforms in science education encourage engaging students in authentic scientific practices (NRC, 2000, 2007) such as scientific modeling. In MoDeLS, we have two overarching

student learning goals for scientific modeling: developing the practice itself and developing the understanding of modeling underlying the practice. Scientific modeling involves a set of modeling practices, including constructing, using, evaluating, and revising models. *Constructing* a model—through identifying the salient features of the system or phenomenon under consideration and determining how those, and the relationships among them, can be depicted or represented—is accompanied by *using* the model to illustrate a system, explain a system or phenomenon, or to make predictions about a phenomenon. This leads to *evaluating* and *revising* models in light of findings so it will better achieve its intended purpose.

Engaging in these modeling practices can promote the development of epistemological metamodeling knowledge (Schwarz & White, 2005) about models and modeling practices, as well as science content knowledge and epistemological understandings of the nature of scientific practice more generally. Indeed, involving learners in modeling practice requires that they understand the rationale for norms that govern the practice (e.g., models need to be evaluated against empirical evidence) to motivate the practice and make learners' engagement meaningful, rather than simply going through a rote sequence of steps. Understanding the purpose of models helps students engage productively in modeling practices (Schwarz & White, 2005; Snir, Smith, & Raz, 2003). Specifically, we try to help learners recognize that models can serve important sense-making and communicative purposes. For scientists, models can provide the means for generating new knowledge. For learners, typically the sense-making purpose of models is more personal—to develop new understandings of a phenomenon and move toward being able to apply those ideas to making predictions about a new phenomenon or a new set of conditions. We use models for three types of work: illustrating a system or phenomenon, explaining a system or phenomenon, or making predictions about a phenomenon.

Scientific modeling, however, is rarely incorporated into educational experiences of elementary or middle school students for anything other than illustrative or communicative purposes. One reason is a lack of high-quality curriculum materials that support the use of scientific modeling. Another reason is that engaging in scientific modeling in the classroom places a high demand on teachers. Most fundamentally, many teachers have limited knowledge of models and modeling (Harrison, 2001; Justi & Gilbert, 2002; van Driel & Verloop, 2002) and also of students' ideas about models and modeling (van Driel & Verloop, 2002). Teachers often see models as useful for teaching about science content, but not about the nature of science (Henze, van Driel, & Verloop, 2007; Justi & Gilbert, 2002; van Driel and Verloop, 2002). Indeed, preservice teachers tend to view modeling through the more familiar lens of the scientific method—and their understanding of modeling is constrained by how tightly they hew to their belief in the scientific method as the gold standard of scientific work (Windschitl & Thompson, 2006). For these and other reasons, many science teachers need support to effectively engage their students in scientific modeling, and perservice teachers need support in being prepared to do so (Crawford & Cullen, 2004; Justi & Gilbert, 2002; Schwarz & Gwekwerere, 2007; Windschitl & Thompson, 2006).

Purpose and Scope of Paper

We work with preservice and inservice upper elementary and middle school teachers to support them in learning to incorporate scientific modeling into their classrooms. We also design curriculum materials that incorporate scientific modeling. Our ultimate goals are to promote student learning of both science content and scientific modeling, and—from a research standpoint—to develop a learning progression describing how students learn about and engage in scientific modeling. Teachers play a crucial role in promoting this student learning. Indeed, we

are embarking on a serious reconceptualization of schooling, one that puts significant stress on teachers learning to engage in new kinds of work. Supporting teacher learning, then, is critical. Here, we describe our efforts toward those ends, with a focus on designing teacher learning experiences and materials that help teachers achieve learning goals associated with modeling.

Teacher Learning Goals for MoDeLS

The MoDeLS framework for teacher knowledge related to scientific modeling informs our learning goals for teachers and guides our designs for promoting teacher learning. Teachers have multiple types of knowledge, including subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge, or PCK (Shulman, 1986; see also Magnusson, Krajcik, & Borko, 1999). While PCK is typically conceptualized as topic-specific, teachers also need discipline-specific knowledge about how a discipline works; for example, teachers need PCK for scientific inquiry (Davis & Krajcik, 2005) and PCK for scientific modeling (Schwarz, Meyer, & Sharma, 2007). Teachers also, of course, need epistemological knowledge (Lederman, 1992)—about the nature of science in general, and about scientific models and modeling in particular.

While all of these types of knowledge are crucial for effective science teachers, the MoDeLS framework focuses on teachers' modeling practices, epistemological metamodeling knowledge (associated with models and modeling practices), and PCK for scientific modeling. PCK for scientific modeling incorporates knowledge of instructional strategies that can promote students' engagement in modeling practices and learning of metamodeling knowledge. PCK for scientific modeling also incorporates teachers' knowledge of their students' ideas and the challenges students face, again associated with modeling practices and metamodeling knowledge. Figure 1 describes our framework for modeling-related teacher knowledge.

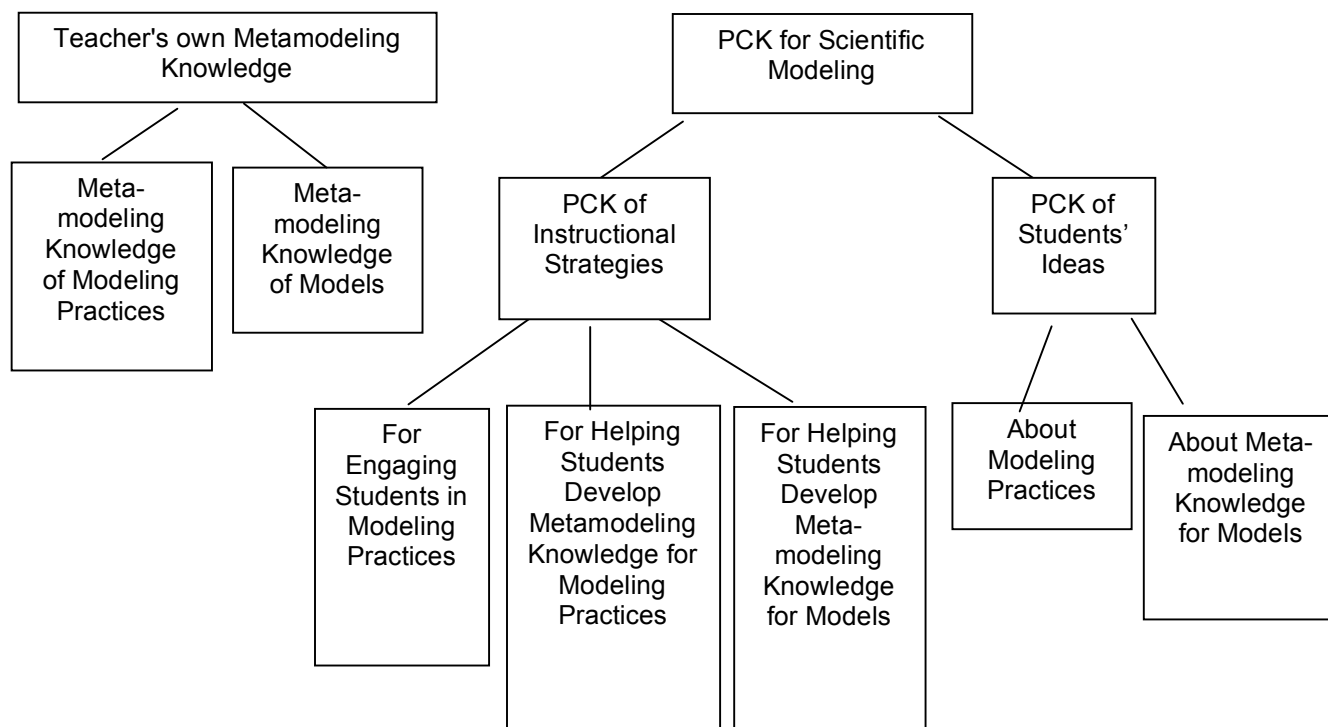


Figure 1: MoDeLS Teacher Knowledge Framework

Our learning goals for preservice and inservice teachers, at the elementary and middle school levels, grow out of this framework. For example, we want teachers to recognize the purpose of models, understand when they might fruitfully engage students in modeling practices, and develop instructional strategies for doing so. Table 1 outlines our learning goals for preservice teachers. (Our goals for inservice teachers are slightly different, and in part reflect differences in the instructional contexts in which we work with them. For example, we work extensively with some of the inservice teachers, and much less closely with others. In addition, preservice teachers face greater challenges in developing this beginning knowledge about engaging students in modeling. Here, therefore, we focus most of our attention on preservice teachers.) Since current reform documents encourage the use of scientific modeling (e.g., NRC, 2007), but do not include standards for teacher learning about scientific modeling, we developed

these teacher learning goals ourselves, based on our analyses of priorities associated with science teaching in general and modeling in particular.

<p>Basic Familiarity with Models and Modeling</p> <ol style="list-style-type: none"> 1. Preservice teachers will gain familiarity with the terms <i>model</i>, <i>idea model</i>, <i>expressed model</i>, <i>modeling</i>, <i>modeling practices</i>, and <i>metamodeling knowledge</i>. 2. Preservice teachers will understand <i>why</i> it is important to engage students in modeling—namely, that modeling is an authentic scientific practice that helps people develop scientific understanding—and will begin to want to do so. 3. Preservice teachers will be able to describe a <i>scientific model</i> as a representation that provides an abstraction and simplification of a system or phenomenon within the natural world and having to do with science that make its central features explicit and visible, allowing someone to generate explanations and predictions of natural phenomena. Preservice teachers will be able to describe what distinguishes a scientific model (such as a model of a molecule or of how light allows us to see) from an everyday model (such as a toy car). 4. Preservice teachers will be able to describe <i>scientific modeling</i> as involving constructing, using, evaluating, and revising scientific models.
<p>Metamodeling Knowledge</p> <ol style="list-style-type: none"> 5. Preservice teachers will begin to recognize distinctions between idea models and expressed models, and will recognize the importance of a teacher using both together (and thus may use "scientific model" to refer to both together). 6. Preservice teachers will begin to be able to recognize the different purposes associated with models. Models can serve as explanatory tools, predictive tools, or illustrative tools. At the same time, models can be used for generating new knowledge and for communicating ideas. 7. Preservice teachers will be able to recognize models in curriculum materials and enacted lessons, included most typically for the purpose of illustrating and communicating ideas. Preservice teachers will be able to recognize that often, such models are developed through someone else engaging in modeling practices and applying metamodeling knowledge, but may be used in instruction without engaging students in the full range of modeling practices or helping them develop their metamodeling knowledge (and thus may help students learn the science content ideas but not as much about modeling).
<p>Modeling Practices</p> <ol style="list-style-type: none"> 8. Preservice teachers will gain experience in modeling practices including constructing, using, evaluating, and revising models. 9. Preservice teachers will gain experience with identifying and using a set of criteria for evaluating an idea model, including criteria such as the model's accuracy, plausibility, consistency, and utility for meeting its intended purpose. They will gain experience with identifying and using a set of criteria for evaluating how well an expressed model communicates the idea model, including criteria such as the model's clarity, the salience of its features, and how well it meets shared norms. They will also be able to recognize the strengths and limitations of each of multiple competing models.
<p>Models and Modeling in Classrooms</p> <ol style="list-style-type: none"> 10. Preservice teachers will begin to be able to identify one or more effective instructional strategies for supporting students in engaging in modeling practices and in developing metamodeling knowledge. 11. Preservice teachers will begin to be able to identify effective instructional sequences that can be used for engaging students in modeling. 12. Preservice teachers will gain experience with analyzing curriculum materials from the standpoint of how well the instructional strategies and/or sequences support students in engaging in modeling practices and in developing metamodeling knowledge.

Table 1: MoDeLS Learning Goals for Preservice Teachers

As an example of what it would look like to achieve one of these learning goals, consider the following example. Teachers may typically believe that models can only be used to

communicate ideas and to illustrate known content. As reflected in learning goals 6 and 7, we hope to support teachers in developing the idea that models can also be used to generate new explanations and predictions—in other words, for a purpose more oriented toward sense-making. For example, a typical use of a butterfly life cycle diagram in an elementary classroom would be to simply represent the canonical knowledge the students had learned about the stages of life of a butterfly. A MoDeLS teacher might help her students use the same diagram for predicting the next stage of life when given, say, a chrysalis.

Similarly, teachers may initially believe that students should accept models (e.g., models used in instruction) at face value. Through engaging in the modeling practices themselves (learning goal 8), teachers may come to recognize that students should evaluate and revise models, using criteria like accuracy, how well the model accounts for evidence, and how well the model communicates the underlying ideas. For example, a typical classroom would use a plastic solar system model to show the planets' order; the size of and distance between is typically assumed (incorrectly) to be to scale. A MoDeLS teacher might engage her students in evaluating how scientifically accurate the model is, using it as a way to help her students think about scale in terms of size and distance. With support, the students could then develop a revised solar system model showing both size and distance to scale.

Learning-Goal Driven Innovations for Promoting Science Teacher Learning

We design learning experiences and materials for preservice and inservice teachers around learning goals. Learning-goals driven design involves three stages of work: specifying learning goals, developing materials, and gathering feedback (Krajcik, McNeill, & Reiser, 2008). While this idea has been introduced in the context of considering student learning, it should be true that teachers, too, benefit from learning-goals driven design. Thus, we use this perspective to

guide our work in designing supports for teacher learning. Specifically, we provide support focused on scientific modeling through educative curriculum materials that promote teacher learning (Davis & Krajcik, 2005) and teacher education experiences. We describe our work in each of these areas, using examples in each to illustrate our learning-goals driven design for supports for teacher learning.

Educative curriculum materials in MoDeLS

Educative curriculum materials are curriculum materials designed with the intention of promoting teacher learning as well as student learning (Ball & Cohen, 1996; Davis & Krajcik, 2005; Schneider & Krajcik, 2002). Our MoDeLS educative curriculum materials cover the range of the MoDeLS framework, in addition to supporting teachers' subject matter knowledge and topic-specific PCK. Our guidance supports teacher learning for engaging students in modeling, within the context of upper elementary and middle school curriculum materials designed with that goal in mind. The educative elements include expository text and narratives situated in lesson plans, and include rationales and implementation guidance. These are educative elements that our prior work has suggested can be effective (e.g., Beyer & Davis, 2007; Davis & Krajcik, 2005; Dietz & Davis, in press; Smithey & Davis, 2004). In addition to these contextualized educative elements, grounded within lesson plans, we have also developed "front matter" for our curriculum materials. "Front matter" refers to the pull-out introductory material with a particular focus in a given set of curriculum materials. Our MoDeLS front matter—intended to introduce the modeling ideas within the various MoDeLS curriculum materials—provides two illustrative examples of how our design is driven by our learning goals for teachers.

First, recall that learning goal 6 relates to understanding the purposes of models. Specifically, we hope teachers will come to understand that models can serve both sense-making

and communication purposes, and that they can be used to illustrate, explain, or predict phenomena or systems. (As noted above, teachers typically recognize the communication purpose of models and the illustrative role they can play, but may not recognize the other purposes they serve and types of work they can do.) Expository text in the front matter explicates the purposes of models with the intention of supporting preservice and inservice teachers who read it in developing more sophisticated notions. Figure 2 provides an excerpt of this text.

After constructing (or revising) a scientific model, students and teachers may **use** their scientific model for a variety of purposes, including **generating or communicating ideas**. By generating ideas, we mean students can use their models to develop knowledge that's new (at least to them); this can also be called using a model for sense-making, and can be done by an individual or group. By communicating ideas, we mean students can use models to share ideas with others. This distinction gets at for whom the model is being used—for oneself or one's group, or for others outside of one's group. Both of these ways of using models are important in science teaching and learning. At the same time models can be used to **illustrate, explain, or predict** systems or phenomena. This distinction reveals the kind of thinking the model is being used to accomplish.

First, scientific models may be used to **illustrate** systems or phenomena that are too difficult to observe directly (for example, phenomena that happen on too large or too small a scale or that cannot be manipulated). For example, the solar system model illustrates, roughly, the relative size of the planets and their order from their sun—a system that is too large to examine in real life.

A more sophisticated use of scientific models is to help **explain** phenomena. In one sense, scientific models can help a person clarify her own understanding of phenomena—as a sort of a “self-explanation” tool that contributes to the generation of new knowledge. Scientific models can also help students develop ideas about relationships between model components. For example, you might ask students to create a diagram of a food web to help them better visualize and keep track of the interactions between predators and prey, producers and consumers, etc. In turn, this food web might inspire you to add aphids to your garden at home in an attempt to keep plant-eating pests under control.

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Finally, scientific models may also be used to **predict** outcomes. In this case, the student will use her model to theorize what the results might be when new experimental conditions or variables (or a new phenomenon or event) are encountered. For example, a student who has developed a model showing how insulation keeps soup warm in a thermos (by slowing the movement of heat) might use her model to predict how the same thermos might keep her drink cold. Again, this use of models can work toward the generation of new knowledge or the communication of existing knowledge.

Figure 2: Example of expository text about the purposes of models

Learning goal 10 is focused on teachers learning to identify one or more effective instructional strategies they can use for supporting students in engaging in modeling practices. For the MoDeLS educative curriculum materials, as noted above, we have developed narrative vignettes. The narrative vignettes are intended to illustrate such effective strategies. These vignettes provide images of the possible; most teachers—especially elementary teachers—have

quite likely never seen or experienced modeling in the classroom, so they have limited vision for what modeling practices can look like when enacted. One of our vignettes describes a fictional elementary teacher engaging in model evaluation with her students. Figure 3 shows this example. (Along with this vignette is additional text explaining criteria along which scientific models can be evaluated.)

MS. GARCIA HELPS HER STUDENTS EVALUATE A MODEL

The students in Ms. Garcia's fourth grade class just finished taking Ms. Garcia's dog, Farfel, on a nature walk in the small forest near the school. When everyone was back in their seats, Ms. Garcia said "Ok, everyone, let's take out our models of forest plant seed dispersal and think about how our models compare to what we observed on our field trip today." Ms. Garcia first had her students discuss their observations as a class, and then each student described how his or her model did or did not explain what they had seen during their nature walk. Bobby showed his model, stating, "I saw squirrels running all over the place and some were burying their acorns. I already had this in my model because I knew sometimes squirrels might forget where they buried an acorn and then you get an oak tree growing." Stephanie shyly said, "I saw lots of prickly seeds stuck in Farfel's fur and so I just thought that there's probably some seeds sticking to the forest animals that have fur too. I didn't draw this in my model because I didn't think of it before." Ms. Garcia assured Stephanie that it was all right, and that she had hoped that the students would learn something new that they hadn't thought of before the forest nature walk. After the presentations, the students identified the similarities and differences among the various models while Ms. Garcia recorded their ideas on the board.

Ms. Garcia talked with the students about how any model has both strengths and weaknesses. She then gave each student a rubric with a list of criteria that they had developed during a previous unit and asked students to work in groups to evaluate how well their models met the criteria, and she reminded them that they would be evaluating the idea models and the picture models. Ms. Garcia circulated to make sure students understood how to apply the criteria and to probe students' evaluations of their models.

Using the rubric allowed the students to see how well their drawings represented their ideas. For example, Drew realized that although he had thought about wind dispersing seeds, none of his classmates could tell where the wind was, because, as Drew noted, wind is invisible so he hadn't drawn it! The class decided to use Amber's wavy lines to depict wind in all their models, setting up an important classroom norm.

Additionally, applying the criteria enabled the students to uncover limitations in how well their idea models were able to account for the scientific phenomena they observed. For example, Shana initially thought that seeds always made new plants right next to the plants that they came from, and did not consider the possibility that animals helped to distribute the plants' seeds. Her group helped her consider that the animal droppings they had seen in the forest contained plant seeds, and also how prickly seeds stick to animals' fur.

Ms. Garcia was very pleased to see her students holding each other accountable for developing models that could represent the phenomena accurately and clearly.

Figure 3: Narrative vignette illustrating a classroom evaluation of models

Here the teacher in the narrative, Ms. Garcia, uses a range of effective instructional strategies for supporting her students in evaluating their models. For example, she has them

identify similarities and differences among the models, she discusses associated metamodeling knowledge (e.g., that models have strengths and weaknesses), she provides them with evaluation criteria (developed earlier), and she supports the evaluation of the idea models and the expressed models. Since teachers typically have little experience with scientific modeling or using it in instruction, illustrating instructional practices in this way can help them add new ideas to their repertoires.

In sum, our design of educative curriculum materials for use with preservice and inservice teachers is guided directly by our learning goals for these teachers. Expository text seems especially useful for developing the teachers' own metamodeling knowledge. Narrative vignettes describing classroom scenarios seem especially useful for developing the teachers' understandings of how these ideas can play out in instruction.

Teacher Education in MoDeLS

In addition to these educative curriculum materials, we have also developed teacher education experiences focused on modeling. We have incorporated these activities into elementary and middle school science methods and content courses for preservice teachers at five universities. For example, preservice teachers engage in modeling experiences; supported by curriculum materials and the teacher educator, they construct, use, evaluate, and revise models (e.g., a model of water movement in plants using celery, water, and dye—a typical modeling experience at the elementary level). Doing so promotes the development of the preservice teachers' own modeling practices—the practices in which we hope they will later engage students—as well as their own metamodeling knowledge. In addition, preservice teachers respond to questions about lessons incorporating modeling to promote reflection about instructional decisions concerning the use of modeling in a lesson. They also engage in

curriculum critique and adaptation (Davis, 2006) using modeling as a lens, and they are encouraged to incorporate modeling into science lessons they enact with children. Experiences like these promote the development of their PCK for scientific modeling.

What does this look like in a science methods class? Engaging the preservice teachers in a science lesson involving the modeling practices allows us to support them in achieving learning goals 8 (about gaining experience with the practices themselves) and 9 (about the evaluating practice and associated metamodeling knowledge). Specifically, in our lesson on water moving through a plant, we had preservice teachers construct, use, evaluate, and revise a model of water movement. First, we asked the preservice teachers to brainstorm a list of elements that they would all want to include in their models of water movement in plants—that is, we scaffolded the development and *construction* of their idea models. Using these elements, the preservice teachers drew their initial picture (i.e., expressed) models of plant water movement. We then asked the preservice teachers to write a brief explanation of their picture model as if they were explaining the phenomenon to a friend. Next, preservice teachers were asked to *use* their models to make a prediction about what would happen when a plant (celery) is placed into colored water. After documenting their observations of celery in colored water, preservice teachers engaged in a whole class discussion to generate a consensus list of criteria for evaluating their models—ideas such as scientific accuracy, completeness, and clarity. The preservice teachers then used each criterion to *evaluate* her own picture model in light of the celery observations. Preservice teachers were asked to consider their model evaluations and the evidence they gathered in the celery experiment to determine whether their initial picture models could be improved or *revised*. Preservice teachers created new expressed models according to their ideas

of what a better model might look like, or—in some cases—decided that their initial models sufficiently satisfied the criteria for a “good” scientific model of plant water movement.

This experience allowed the preservice teachers to move through the entire range of modeling practices. (A similar lesson with preservice teachers used the formation of dew as the scientific context.) They were able to then apply some of those ideas—especially the evaluation of models—in an assignment we gave them in which one portion asked them to evaluate examples of student models of germ transmission, providing further work related especially to learning goal 9. We used a new content area here to increase the range of contexts in which preservice teachers experienced models and modeling.

The other portion of the germ transmission assignment, completed in class, focused on learning goal 12: analyzing curriculum materials using the lens of scientific modeling. We provided preservice teachers with a typical, content-focused use of modeling in an elementary classroom—namely a physical simulation of the phenomenon of germ transmission (in this case, using flour to represent germs and having individuals shake hands to show the transmission of the germs). The preservice teachers were asked to describe what changes, if any, they would make to the lesson to better engage students in scientific modeling and to promote their understanding of metamodeling knowledge.

Some preservice teachers at each site also chose to incorporate modeling into the lessons they were developing to teach elementary or middle school students. The preservice teachers who did so were given different guidelines at the different sites, depending on programmatic constraints and goals, but essentially preservice teachers were asked to either develop a lesson “from scratch” or were given a lesson, typically from their cooperating or mentor teacher, to adapt and, in most cases, teach. This process allowed the preservice teachers to work on

identifying effective instructional strategies (learning goal 10) and instructional sequences (learning goal 11) for engaging students in scientific modeling. While preservice teachers differed in how well they were able to achieve these goals (Hug et al., in preparation), the endeavor did allow them to begin the work of considering these ideas instructionally when considering their own classrooms and students.

In sum, as with our design of educative curriculum materials, our work in designing teacher education experiences for preservice teachers is guided by our learning goals for them. In the teacher education experiences, we are better positioned to support the development of the teachers' own abilities related to the modeling practices (which we cannot address through the educative curriculum materials) and also of their associated instructional practices.

Design Challenges

Despite success in developing and using these supports for teacher learning, we also face design challenges. In both teacher education and educative curriculum materials, whatever time or space we allot to scientific modeling means time or space taken away from some other overarching learning goal. Teacher educators' time with preservice teachers is too limited already (Clift & Brady, 2005); indeed, teacher education has a relatively short period of specialized schooling compared with other professions (Lortie, 1975). Infusing learning goals associated with scientific modeling further limits the time available to spend on other crucial learning goals, such as those associated with assessment or equity. At the same time, it might also lead teachers to value only modeling, at the expense of other kinds of scientific work, in their science teaching. Yet the most successful examples of engaging preservice teachers with modeling and at least marginally changing their beliefs have involved far more extensive interventions than we are

able to develop (e.g., Schwarz et al., 2007; Windschitl & Thompson, 2006), leading us to emphasize the importance of prioritization.

How can teacher educators decide which learning goals are highest priority? We attempt to address a few big ideas related to modeling. We made our decisions about where to focus by weighing a set of considerations—namely time, leverage, and tractability. Given time as a constant constraint, we tried to identify high-leverage ideas. For example, since our research group discussions kept returning to the idea of the purpose of models and modeling, we recognized the importance of that idea and incorporated it as a learning goal (#6). At the same time, we tried to identify ideas with which teachers—especially preservice teachers—were likely to be able to get traction. A focus on the modeling practice of evaluation, then, seemed appropriate (learning goal #9). This idea is high-leverage, in that engaging in model evaluation naturally leads to model revision, and also helps to promote the idea of a dynamic nature of science more generally. Evaluation is also high-leverage in that engaging in the practice very naturally brings in the metamodeling knowledge—this forces learners (including teacher learners) to use the metamodeling knowledge within the practice. At the same time, the idea of model evaluation is tractable, in that evaluation criteria can be identified and used relatively straightforwardly.

Similarly, a design challenge inherent in adding teacher learning supports into curriculum materials is that the materials quickly get too long to be tenable for teachers' use (Davis & Krajcik, 2005). While teachers need support in learning to engage students in modeling, adding too much support will contribute to the problem of the ever-expanding length of educative curriculum materials. How can curriculum designers decide what is most important to support? We are working to determine an appropriate level and sequence of support.

Finally, we note the design challenge associated with any work with teachers—that they need to learn something new and at the same time learn how to put those new ideas into practice. In this case, teachers are learning *about* modeling, learning to *use* those new ideas as they *engage in modeling*, and learning to *engage students in modeling*—a tall order. Even developing both the metamodeling knowledge and using it in scientific practice—absent the instructional application—is challenging. In a study of preservice secondary science teachers with undergraduate backgrounds in science, even the preservice teachers with stronger metamodeling knowledge had trouble using their models in scientific inquiry (Windschitl & Thompson, 2006). The cognitive demands of engaging students in scientific modeling are high for any teachers, and particularly for preservice teachers. We struggle to determine the appropriate balance between helping the teachers develop their own metamodeling knowledge and modeling practices, on the one hand, and developing abilities associated with incorporating those ideas into their own instructional practice, on the other. Our pilot work indicates that while our supports are helpful in some ways, we certainly still have room to improve our approaches (Hug et al., in preparation). As with any work in learning-goal driven design, empirical feedback on the efficacy of the designs is an important component (Krajcik et al., 2008).

Implications and Conclusions

We recommend that science teacher educators consider a learning-goal driven approach in developing learning experiences for teachers. Rather than taking an activity-driven approach, teacher educators must consider what they want teachers to learn, and then carefully design learning experiences to support that learning (Davis & Smithey, in review; Grossman, 2005; Russell & Martin, 2007).

We emphasize, as well, that science teacher educators must support teacher learning when we place new expectations on teachers. For example, *Taking Science to School* (NRC, 2007) describes a new definition of scientific proficiency. Without taking seriously the notion that teachers must learn to engage students in work that would help them develop that new proficiency, the reform recommendations are doomed to fail. When we engage in such serious consideration of supporting teacher learning, however, we have the potential for re-inventing K-12 science instruction.

We are asking for some fundamental shifts in how teachers think about using models in classrooms—no easy task (Loughran, 2007). Rather than a stance that models are something to be provided or shown to students, we argue that teachers should engage students in constructing models toward the goal of illustrating, explaining, and predicting phenomena. Rather than a stance that models should be accepted as is—as the status quo representation of the known scientific facts—we argue that teachers should engage students in evaluating and revising models, to help them develop a better understanding of how science works. And rather than a stance that models stand alone, we argue that teachers must incorporate discussions of models and modeling to help students develop that improved understanding. These all may require reconceptualization on the part of the teachers (Henze et al., 2007; Justi & Gilbert, 2002; van Driel & Verloop, 2002), especially when the teachers themselves may not have extensive experience in the doing of science. Supporting these shifts and reconceptualizations, then, is paramount.

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