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MoDeLS

Challenges in Defining a Learning Progression for Scientific Modeling

The MoDeLS project, *Modeling Designs for Learning Science,* has been developing and refining a learning progression that represents successively more sophisticated levels of engagement in the practice of scientific modeling (Schwarz et al., 2009). Our view of modeling practice draws on areas of agreement in current studies of learning about modeling (Harrison & Treagust, 2000; Lehrer & Schauble, 2000, 2006; Lesh & Doerr, 2003; Lesh & Lehrer, 2003; Treagust, Chittleborough, & Mamiala, 2002). We define a scientific model as an abstract, simplified representation of a system that makes its central features explicit and visible and that can be used to generate explanations and predictions (Harrison & Treagust, 2000). Examples of different kinds of scientific models include the Bohr model of the atom, the particle model of matter, a light ray model for how we see objects, the water cycle model, and a food web model indicating interactions between organisms. Working with scientific models involves constructing and using models as well as evaluating and revising them. The goal of this practice is to develop a model consistent with theoretical and empirical evidence that can be used to explain and predict multiple phenomena.

Developing and using models is central to authentic scientific practice. Involving learners in the practice of scientific modeling can help them construct subject matter knowledge, epistemological understanding, and expertise in building and evaluating scientific ideas (Lehrer & Schauble, 2006; Lesh & Doerr, 2000; Schwarz & White, 2005; Stewart, Cartier, & Passmore, 2005). The opportunity to engage in scientific modeling is important for developing and evaluating explanations of the natural world. Scientific modeling, however, is rarely incorporated into the educational experiences of elementary or middle school students. When modeling is part of school experiences, it is often reserved for secondary students and is primarily used for illustrative or communicative purposes, thus limiting the epistemic richness of the scientific practice (Windschitl, Thompson, & Braaten, 2008).

Our goal is to develop a learning progression that characterizes the aspects of modeling that can be made accessible and meaningful for students and teachers in upper elementary and middle school classrooms – ideally, a learning progression that can be used across multiple science topics and can support development of the practice across multiple years of learning. Consistent with other chapters in this

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book, we view a learning progression as a framework for articulating successively more sophisticated versions of knowledge and practice that is built on the understandings and ways of knowing that learners bring to the classroom (National Research Council [NRC], 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Learning progressions offer the opportunity to explore and characterize paths through which students can build their knowledge and practices over time across a variety of important contexts such as different curriculum materials and classroom environments. Learning progressions are useful for designing effective instructional materials, designing formative and summative assessments, and supporting instruction that can help learners meaningfully engage with science ideas and practices over time. We do not assume that students become more sophisticated at engaging in the practice of scientific modeling in a particular fixed sequence. Progress may take different paths as students build sophistication with respect to the various elements of modeling practice. We expect that learners' enactment of modeling practice is critically dependent on instruction and scaffolding (Lehrer & Schauble, 2006; NRC, 2007). Thus we do not claim that the elements of modeling practice we describe are context-independent.

We have chosen to foreground the scientific practice of modeling in our learning progression. While we recognize the content-dependent nature of scientific practices, our research project has chosen (1) to focus on an important scientific practice that, with some exceptions (e.g., Lehrer & Schauble, 2000), is not typically highlighted in most elementary and middle school classrooms, (2) to determine whether students can abstract aspects of the practice across science topics over time, and (3) to conduct research in elementary and middle school science contexts that typically include teaching multiple science topics (in physical, life, and earth science) each year.

We developed our learning progression through an iterative process involving theoretical and empirical work. We began with consideration of prior theoretical analyses, empirical investigations, and work in philosophy of science; subsequently, our work has been guided by our empirical research from classroom enactments of modeling-oriented curriculum materials and assessments in upper elementary and middle school classrooms (Schwarz et al., 2009). This iterative process of designing a learning progression started with defining an initial framework in conjunction with designing curriculum materials and assessments used in the first year of the classroom enactments. The framework was then fleshed out with our initial empirical data and revised to become our initial learning progression (Schwarz et al., 2009). We subsequently refined our curriculum materials and assessments for classroom enactments in the second year and used the outcomes of these enactments to further revise our learning progression.

There are many challenges associated with building a learning progression for a complex practice such as scientific modeling. The development of an empirically-supported learning progression for a scientific practice is a paradigmatic example of research problems suited to design research (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Edelson, 2001). Characterizing and comparing possible paths for learning a particular target concept are not solely matters of empirical investigation. Defining the target of learning involves design considerations. The goal in bringing scientific practices into classrooms is not simply to replicate professional practices; rather, it requires exploring which aspects of a given practice are both feasible and productive for learners (Edelson & Reiser, 2006). Investigations of pathways through which students can develop a scientific practice require empirical explorations of challenges and successes in reaching particular learning goals and entail developing design arguments for the learning goals. Design research is also essential because the target practice rarely exists in typical classrooms; investigations of the practice require design decisions aimed at creating the conditions that can support it (Cobb et al., 2003).

In this chapter, we explore design challenges that emerged in attempting to define, investigate, and revise a learning progression for scientific modeling. We consider issues in *defining* the progression, including which elements of modeling practice are critical for learners, which dimensions of the practice should be represented in a learning progression, and what grain size is needed to capture change. We also consider issues involved in *investigating* the learning progression such as designing effective curriculum and professional development materials to support teachers and students in their enactments of the practice. Investigating the learning progression also requires effective assessments across multiple science topics and appropriate analytical tools for interpreting outcomes. Finally, *revising* the learning progression requires analyzing students' work as they engage in modeling practices. We outline the challenges we faced in our process of defining, investigating, and revising our progression. We also present the learning progression we developed through this iterative design process.

CHALLENGES IN DEFINING A LEARNING PROGRESSION FOR THE PRACTICE OF SCIENTIFIC MODELING

Challenges in Defining the Aspects of Scientific Modeling for Classrooms

Scientific modeling is a rich practice that overlaps with other practices such as conducting investigations, constructing explanations, and engaging in argumentation (Passmore & Svoboda, 2011). Educators could choose to involve learners in a variety of candidate forms of scientific modeling. Hence one challenge in designing a learning progression for modeling is to identify which forms of modeling (with their underlying knowledge) are appropriate and productive for learners in school science settings. In particular, what aspects of modeling can (and should) learners understand and be able to do? Research on bringing scientific practices into classrooms has focused on practices such as argumentation, explanation, and scientific modeling. This work contains common elements, such as comparing alternatives, community building of knowledge involving argumentation and consensus, and evaluating scientific ideas against evidence. However, the research differs in the specific analytical frameworks used to characterize the target practice. Some modeling approaches focus on models as embodying patterns in data (Lehrer & Schauble, 2000) while others discuss models as embodying causal explanatory mechanisms for phenomena (White, 1993;

Windschitl et al., 2008). There are also open questions about conceptualizing learning goals such as whether to prioritize knowledge about the practice (Lederman, 2007) or the practical work of knowledge building through use of the practice (Sandoval, 2005).

To address the challenge of deciding which elements of the practice are suitable and productive for learners, we made several design decisions that influenced our learning progression. These included decisions about highlighting particular forms of models and elements of modeling practice, balancing metaknowledge and practice, and studying the practice across science topics. Our design decisions were based on prior research (Carey & Smith, 1993; Lehrer & Schauble, 2000; Schwarz & White, 2005; Stewart et al., 2005), theoretical arguments for what is most productive for learners (Schwarz, 2002), and contextual constraints such as what is possible in classrooms with existing curriculum materials and teachers.

Highlighting particular forms of models. We chose to design a learning progression that engages learners in modeling components, processes, and mechanisms that can explain and predict phenomena. The focus of modeling in our learning progression contrasts somewhat with a focus on modeling data or patterns in data (e.g., Lehrer & Schauble, 2000). Data modeling is central in science (e.g., much of modern science involves data and computational modeling) and enables a focus on the mathematical and representational aspects of making sense of phenomena. We chose a complementary focus – namely models that embody some aspects of causal and often non-visible mechanisms or explanatory components (Clement, 2000; White, 1993). Like data modeling, this type of modeling involves learners in creating, debating, and reaching consensus on inscriptions that represent their thinking about scientific phenomena (Lehrer & Schauble, 2004, 2006). We focus on explanatory models to emphasize accounting for patterns in phenomena by proposing theoretical explanatory constructs, such as processes and mechanisms, which are a critical part of building knowledge in science (Russ, Scherr, Hammer, & Mikeska, 2008). Examples of these explanatory constructs include (a) using reflection, absorption, and transmission of light rays as mechanisms to explain shadows, reflection, color, and other phenomena and (b) using the presence and movement of particles of matter as mechanisms to explain phase changes, diffusion, and related chemical phenomena.

Targeting explanatory constructs and mechanisms in students' models is certainly ambitious. Students' ideas about causes of scientific phenomena are typically under-developed. At times their ideas are consistent with their perceptions from everyday experiences but inconsistent with scientific data and canonical explanations. However, modeling allows students to externalize and reflect on evidence and experiences and to relate them to possible mechanisms and additional scientific information. In this way, students can move toward higher-level explanations and predictions of phenomena.

Selecting elements of modeling practice. Our learning progression reflects the commitment that learners need to engage in the modeling practice itself: embodying key aspects of a theory and evidence in an expressed representation; using the representation to illustrate, predict, and explain phenomena; and evaluating and revising the representation as it is used. While teachers may provide learners with models for observing aspects of phenomena or have learners construct models to apply what they have been taught, engaging learners in the evaluation and revision of models is rare. Yet this entire model construction and revision process—also called model evolution (Clement, 2008) or model refinement (Acher, Arcà, & Sanmartí, 2007)—is critical for a better understanding of and participation in science. Students need the opportunity to evaluate and revise their models if they are to understand the relationship between models and data, as well as the social aspects of the modeling process (Clement, 2008; White & Frederiksen, 1998). As students engage in elements of modeling practice, they must attend to the role of empirical evidence in constructing, evaluating, and revising models. The social context is critical to motivating and supporting the evaluation and revision of models since the generation of competing alternative models creates a need for criteria to evaluate the strengths and weaknesses of candidate models. In addition, students use the audience of their classroom peers to test the effectiveness of their models for persuading others and helping them to understand targeted scientific ideas.

Drawing on prior work related to epistemologies and the nature of science (Carey & Smith, 1993) and on student learning about modeling (Grosslight, Unger, Jay, & Smith, 1991; Snir, Smith, & Raz, 2003; Spitulnik, Krajcik, & Soloway, 1999; Stewart et al., 2005), we operationalized the practice of modeling to include four elements:

- *Constructing* models consistent with prior evidence and theories to illustrate, explain, and predict phenomena;
- *Using* models to illustrate, explain, and predict phenomena;
- Comparing and *evaluating* the ability of different models to accurately represent and account for patterns in phenomena and to predict new phenomena; and
- *Revising* models to increase their explanatory and predictive power, taking into account additional evidence or aspects of phenomena.

These four elements represent modeling tasks that can be differentiated by their goals and guiding criteria, but they are not discrete steps performed in sequence. For example, students may compare and evaluate candidate models as they attempt to revise their current model. These four elements provide the foundation for the modeling practice in our learning progression.

Balancing and integrating metaknowledge and practice. Our goal is to engage learners in reflective practice in which scientific activity is meaningful to them (Edelson & Reiser, 2006; Lehrer & Schauble, 2006; Lehrer, Schauble, & Lucas, 2008). Achieving this goal requires supporting both the doing and the understanding of the practice (metaknowledge). To guide instruction and assessment, the learning progression must articulate learning goals that involve both performance of the elements of the practice and the associated metaknowledge. An important design tradeoff emerges when selecting and integrating metaknowledge into a practice. On the one hand, we do not want to teach modeling as a scripted routine in which students perform steps simply because they were encouraged to do so in instruction. In contrast to learned routines, engagement in a practice is governed by shared understandings, norms, and goals – the form of practice is meaningful to the community engaged in that practice (Bielaczyc & Collins, 1999; Brown & Campione, 1996). This motivates the need for including elements of metaknowledge as part of modelling instruction. The underlying epistemological understanding explains why the practice takes the form and develops the way it does. For example, constructing scientific explanations is more sensible when learners understand how everyday explanations differ from scientific explanations; while plausibility is a sufficient criterion for everyday explanations, scientific explanations must also be consistent with empirical evidence (Brewer, Chinn, & Samarapungavan, 1998). This argument suggests that understanding how and why models are used, as well as their strengths and limitations, may help learners construct, use, evaluate, and revise their own and others' models (Schwarz, 2002; Schwarz & White, 2005; Schwarz et al., 2009).

On the other hand, there are many ways of exploring how science works and how scientists think that challenge learners' prior understandings (Abd-El-Khalick et al., 2004; Lederman, 2007). Making modeling practice meaningful is our foremost goal. Thus we do not want to target knowledge about the nature of science as a learning goal for its own sake. Teaching nature of science ideas without embedding them in practice risks them becoming decontextualized knowledge that is not grounded in students' own experience of engaging in the practice. Thus there is a tension between including those elements of metaknowledge that can help make the practice meaningful (rather than a scripted routine) and including metaknowledge that may become a set of decontextualized facts simply to be learned.

Our design strategy involves a pragmatic instrumental approach to metaknowledge in which we focus on the metaknowledge that is useful in helping learners resolve the obstacles they encounter (Sandoval, 2005). This is a learning-for-use argument in which the utility of scientific ideas arises as they are introduced to help learners solve problems they are investigating (Edelson, 2001; Kanter, 2010). In this way, learners construct scientific ideas as tools for solving meaningful problems, rather than ideas to be learned for their own sake. We adapt this idea by situating the teaching of the metaknowledge in modeling problems that the metaknowledge can help guide. Therefore, our learning progression specifies the elements of metaknowledge that we theorize influence the elements of modeling practice. We look for and support growth of metaknowledge as it applies to the performance of elements of modeling practice.

Thus in articulating metaknowledge in practice (*metamodeling knowledge*; Schwarz & White, 2005), we focus on elements that help students make modeling decisions. For example, when comparing competing ideas to develop group consensus, knowledge about criteria for evaluating models, such as fit with empirical evidence about phenomena and coherence of explanation, is needed to tackle the modeling work. Other metaknowledge may be possible to target—such as the understanding that models can take different forms; knowlege of relationships among and differences between models, theories, and laws; and more general ideas about scientific disciplines involving "creativity" (Lederman, 2007)—but these ideas have less clear utility in guiding students' construction, comparison, evaluation, and revision of models.

Conceptualizing modeling as a general scientific practice. A related issue in balancing the performance of elements of practice and metaknowledge is the level of abstraction of the reflective practice targeted for instruction and hypothesized to improve with experience. For example, to what extent can students use the same reflective practice in constructing, using, evaluating, and refining models about heredity, the nature of matter, and ecosystems dynamics? The influence that specific scientific disciplines and types of investigations have on learning scientific practices is critical (Lehrer & Schauble, 2006; Tabak & Reiser, 2008). Engaging in a practice is always situated in particular disciplinary investigations that vary along important dimensions. For example, designing experimental investigations (such as studies of the relationship between force and motion of physical objects) is different from designing investigations that require the analysis of naturally occurring datasets to determine relationships between variables (such as longitudinal studies of species interactions in ecosystems). This difference suggests that the approach taken in defining learning progressions could focus on the combination of a practice and a domain, such as scientific modeling in physical science.

We view these discipline-specific practices as important specialized forms of more general practices, such as the scientific evaluation of the relationships between two variables. Thus, for both instruction and analysis, we target general aspects of constructing mechanistic models that cut across specific scientific disciplines – e.g., evaluating fit with evidence, focusing models on the salient details that support explanations, and generalizing the model to explain a range of cases. This focus allows us to explore how the practice can become more sophisticated across a range of scientific ideas. To determine whether the reflective practice of modeling transfers from one setting to another, we examined whether that practice could be applied across a wide range of scientific phenomena.

These decisions to integrate performance of elements of practice and metaknowledge across multiple science topics have important implications for defining, investigating, and revising the learning progression. In the following sections we discuss the challenges that arose in making these decisions.

Challenges in Defining an Initial Learning Progression for Scientific Modeling

We represented our initial learning progression for scientific modeling as a set of related construct maps (Wilson, 2005, 2009), each of which represents a trajectory of the elements of this practice and associated understandings that we expect students to exhibit in classroom modeling activities. Each level in our construct maps represents a more sophisticated version of the previous level; thus these construct maps represent the theoretical articulation of the elements of performance and understanding of the practice that become more sophisticated with experience and instruction. The construct maps then guided the design of supports for learning and analyses of student growth over time. We used these construct maps to develop more specific rubrics for analyzing a range of data from classrooms. Our data included student interviews, written assessments, and classroom discourse in small group work and in whole class discussions. Analyses from multiple enactments helped refine the theoretical articulation of the construct maps.

One important challenge in defining our initial learning progression involved the dimensions of the learning progression (i.e., which construct maps to include) and the grain size for each dimension. We initially considered creating construct maps that represent the combination of each of the four elements of practice and several relevant elements of metamodeling knowledge (such as the purpose and nature of models and the criteria for evaluating models). However, there would have been overlapping elements of practice and similar metamodeling knowledge in these maps. For example, the use of models to explain phenomena motivates both the construction and the use of models. The fit of the model to evidence applies to both the evaluation and the revision of the model. Furthermore, the elements of the practice refer to tasks that may overlap. Constructing models and using models to explain phenomena may be separate steps, for example, when using an existing model to explain a new although similar phenomenon. However, constructing models and using models can also be coordinated tasks since considerations of whether a model sufficiently explains the data about a phenomenon should guide decisions in constructing that model. Similarly, evaluating a model's strengths and weaknesses and revising that model may either be two steps in the same task or two separate tasks.

Thus, rather than creating separate construct maps for each element of the practice combined with associated metamodeling knowledge, we identified two clusters of issues that synthesize metamodeling knowledge and that influence the four elements of practice. Those clusters were represented by the two dimensions of our initial learning progression and are illustrated by two construct maps that describe these aspects of reflective practice. Thus each construct map describes aspects of students' modeling performances (such as their decisions about revising models, properties of their constructed models, or changes in a revised model) and their reasoning about these performances (as reflected in their classroom discourse or written explanations). The *generative* dimension (Table 1) describes the reflective practice for how models predict or explain aspects of phenomena when models are constructed or used. Each target is defined as a combination of students' performance of a modeling task (both process and product) and the underlying metaknowledge that makes the activity meaningful. The *dynamic* dimension (Appendix) describes reflective practice for when and how models need to change when students evaluate and revise them (see Schwarz et al., 2009 for additional details about our initial learning progression). These two dimensions provided the initial framework that guided our empirical investigation of modeling practice in the classrooms.

In our initial generation of the construct maps, we defined levels associated with significant, rather than incremental, differences in reflective practice, resulting in broad descriptions. These levels were based on prior theoretical and empirical work (e.g., Carey & Smith, 1993; Schwarz & White, 2005) that outlined broad categories of meaningful change. Since we were uncertain about what we might detect in students' work as they engaged in modeling practice, we developed broad descriptive levels. Our intent was to revise the level descriptions in response to empirical data. As a result, differences between levels in our construct maps represent significant shifts in reflective practice based on different epistemological notions of modeling. We included several levels, or general descriptions of reflective practice, that are qualitatively different and are associated with aspects of practice that might be valuable in a scientific context. The first level of each construct map embodied the initial description of modeling practice – envisioned as engaged in by learners in early elementary school or by learners with no prior modeling experiences. The final (fourth) level was associated with advanced ideas about and sophisticated use of modeling – envisioned as the practice of experienced college science students, graduate students, or scientists – and helped us outline the possible levels of modeling practice. We also included two intermediate levels: a second level for learners who have moved beyond a beginning phase but still engage in epistemologically limited modeling practice and a third level for learners who have shifted toward more sophisticated understanding and modeling practice.

Table 1. A Construct Map for the Generative Dimension: Understanding Models as Generative Tools for Predicting and Explaining.

Level	*Descriptions of Reflective Practice (Including Performance of Elements of the Practice and Associated Metaknowledge)*
4	Students *construct and use models, extending them* to a range of domains to help their own thinking. Students *consider how the world could behave according to various models*. Students construct and use models to generate new questions about the behavior or existence of phenomena.
3	*Students construct and use multiple models to explain and predict additional aspects of a group of related phenomena*. Students view models as tools that can support their thinking about existing and new phenomena. Students consider alternatives in constructing models based on analyses of the *different advantages and weakness* for explaining and predicting these alternative models possess.
2	*Students construct and use a model to illustrate and explain how a phenomenon occurs*, consistent with the evidence about the phenomenon. Students view models as a *means of communicating their understanding of a phenomenon* rather than as tools to support their own thinking.
1	*Students construct and use models that show literal illustrations of a single phenomenon*. Students do not view models as tools to generate new knowledge but do see models as *a means of showing others what the phenomenon looks like*.

Note. Adapted from "Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners," by C. V. Schwarz, B. Reiser, E. A. Davis, L. Kenyon, A. Acher, D. Fortus, Y. Shwartz, B. Hug, and J. Krajcik, 2009, Journal for Research in Science Teaching, 46, p. 640. Copyright 2009 by Wiley Periodicals, Inc. Reproduced with permission of Wiley Periodicals, Inc. via Copyright Clearance Center.

Consider the construct map for the generative dimension, shown in Table 1. This dimension describes how students construct and use models that embody explanatory constructs (e.g., mechanisms, processes) and whether students view models as useful for advancing their own knowledge as well as for helping communicate what has been learned to others. One challenge we faced in constructing this map was aggregating aspects of the practice that generally represent similar epistemological ideas while addressing different decisions surrounding the practice, such as the audience or the type of model constructed or evaluated. We aggregated several aspects under each level based on preliminary classroom data that suggested aspects that either clustered or seemed to play an important role at a particular level.

Each of the four levels shown in Table 1 is defined by two related descriptions. The first description is intended to capture the sophistication of students' construction and use of models and the associated metaknowledge that guides their decisions about the model components and the relationships between these components. The second description focuses on students' understanding of the reasons for constructing and using models. All indicator statements include performance of the elements of the practice guided by associated metaknowledge. We next describe these four levels using examples of student work from classroom enactments in which modeling curriculum materials were used.

We designed the Level 1 descriptions to capture students' reflective practice characterized by considering modeling and the purpose of models to be literal illustrations of a particular phenomenon. For example, Figure 1 shows a fifth grade student's pre-instructional model of water in a covered and uncovered cup. The student drew a model that shows the water level before and after a period of time but that includes no explanatory components. Students at Level 1 make their models as similar to the real thing as possible. For example, a fifth grade student commented (after an introductory modeling unit): "A model would [be] like an actual Coke can with water on the side, or a picture of it, that is more detailed and colored …"

We designed the Level 2 descriptions to capture students' reflective practice characterized by (1) constructing and using models to explain how phenomena occur and (2) making their models consistent with evidence about the phenomena. This level is more sophisticated because students construct and use models that include non-observable processes and mechanisms. Students at this level also consider sources of information such as empirical evidence or information from teachers and books. However, students at this level do not yet view models as tools to support their thinking. After the modeling unit, the same fifth grade student (who drew the model in Figure 1) drew the model in Figure 2. In Figure 2 the student drew microscopic particles in a "zoomed-in" fashion to illustrate how the water condenses and escapes. The student also drew arrows that indicate a process and direction for the evaporation and labels that show the water level has changed in the uncovered cup (i.e., a change over time). Students at this level justify changes to their models in general terms of the model's ability to explain phenomena. For example, this fifth grade student commented after the modeling unit: "The models are helpful because they explain how evaporation and condensation works." This example illustrates how a student's level in the construct map can change after instruction.

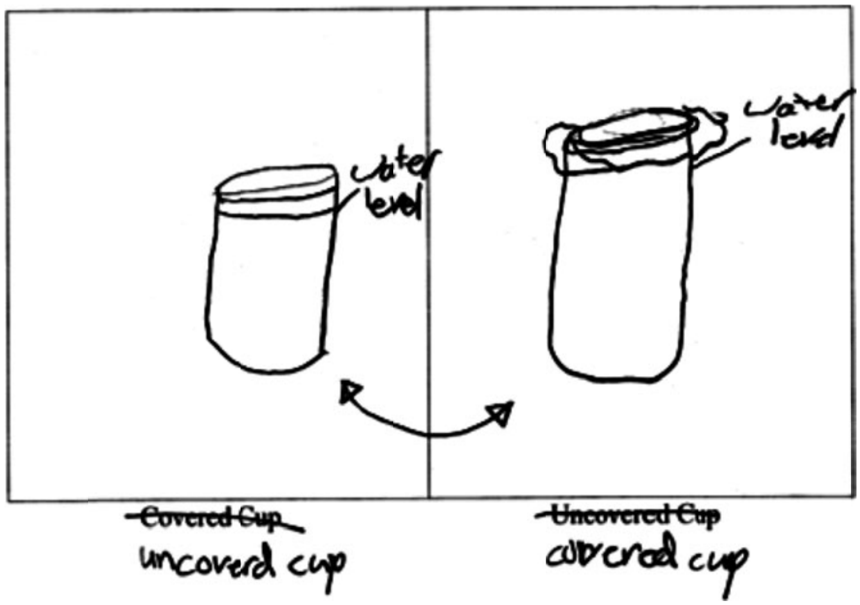

Figure 1. A fifth grade student's pre-instruction model to show what happens to water level in a covered cup and in an uncovered cup (Level 1 on the generative construct map).

We designed the Level 3 descriptions to capture students' reflective practice characterized by using models not only to explain phenomena they observe but also to make predictions about new phenomena. At this level, students view models as thinking tools. Since students' models explain a cluster of related phenomena, multiple models may be required. Students may consider alternatives when constructing models and choosing model components. We see some aspects of Level 3 reflective practice when students apply explanatory models to predict other phenomena that go beyond the situations they used to construct them. Consider this excerpt from an interview with a sixth grade student that occurred during a chemistry modeling unit:

> **Interviewer**: Could a model like the models you have done help you to understand something that you don't know yet? Just to predict?
>
> **Student**: Yes, I think that we could use these models to show about a different gas. Because I think air is also a type of gas. So if we know what air does and has in it and how it moves when other things come in its way and everything, we could find out what other gases also do because they could be similar to air.

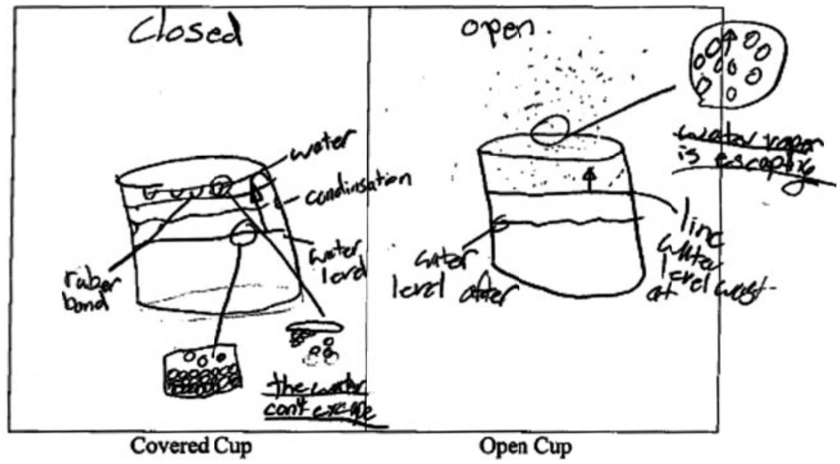

Figure 2. The same fifth grade student's post-instruction model of water in a covered cup and in an uncovered cup (Level 2 on the generative construct map).

We designed the Level 4 descriptions to capture students' reflective practice characterized by constructing and using models that extend to a range of domains in order to advance their thinking. Students consider how the world *could* behave according to various models, and they construct and use models to generate new questions about phenomena. We have found no examples of this type of reflective practice in our elementary and middle school classroom enactments. However, using models to advance scientific knowledge by generating questions to guide research is fundamental to knowledge building in science (Carey & Smith, 1993; Lederman, 2007; Lehrer & Schauble, 2006) and forms an important placeholder for envisioning more advanced forms of modeling practice. Examples of such reflective practice have been shown to exist in other settings (Fortus, Rosenfeld, & Shwartz, 2010; Smith, Maclin, Houghton, & Hennessey, 2000).

CHALLENGES IN INVESTIGATING THE LEARNING PROGRESSION

We engaged in an iterative process of investigating and revising our initial learning progression with data from multiple classroom enactments as part of an empirical validation process (Mohan, Chen, & Anderson, 2009). We analyzed classroom enactments that occurred over two years in fourth, fifth, and sixth grades in three Midwest states, using scientific modeling curricula we developed or adapted to support teachers' and students' engagement in the practice. We collected and analyzed evidence of students' reflective practice from written pre-post assessments, videos and written artifacts from classroom enactments, and student interviews.

Scientific modeling can be complex and difficult for teachers and students (Justi & van Driel, 2005; Schwarz et al., 2009; van Driel & Verloop, 1999; Windschitl et al., 2008). Teachers frequently struggle with understanding what constitutes a scientific model, how to productively incorporate modeling into the curriculum, and how scientific modeling overlaps with other scientific practices emphasized in state and national standards, such as scientific inquiry and generating explanations. Consequently there have been several major challenges in our use of classroom enactments to generate evidence to investigate our learning progression. In particular, we faced challenges (1) in designing and adapting curriculum materials to investigate a learning progression for a practice, (2) in working with teachers to better understand and incorporate scientific modeling in their teaching, and (3) in designing assessments that adequately assess students' engagement in the practice.

Challenges in Designing and Adapting Curriculum Materials

The investigation of learners' engagement in a scientific practice and of the elements of performance and understanding that become more sophisticated over time requires sustained opportunities to engage in the practice with targeted support. Unfortunately, students rarely have the opportunity to engage in knowledge-building scientific practices such as explanation, modeling, and argumentation (NRC, 2007; Weiss, Pasley, Smith, Banilower, & Heck, 2003). Thus investigating a learning progression for a scientific practice requires a research program that studies what is possible for learners to accomplish with support, rather than one that studies what "naturally" emerges as learners participate in typical instruction and out-of-school experiences. Learning progressions for scientific practices do not describe developmentally inevitable stages; rather, they describe what learners can accomplish with suitable learning opportunities for engaging in a given practice and with appropriate support for engagement and reflection. Thus, to investigate a learning progression for scientific modeling, we had to create suitable instructional contexts. We had to make several choices in this effort: the selection of scientific topics in which to embed the practice; the decision of whether to design or to adapt the curriculum; and the identification of the practice elements to highlight.

Selecting scientific topics for modeling. As discussed earlier, we define modeling, as other researchers do (Harrison & Treagust, 2000; Lehrer & Schauble, 2000, 2006; Lesh & Doerr, 2003; Lesh & Lehrer, 2003; Treagust et al., 2002), as an abstract, simplified representation of scientific phenomena that makes the central features of the phenomena explicit and that can be used to generate explanations and predictions (Harrison & Treagust, 2000). Other work has explored how to help students develop explanations for phenomena and support those explanations with scientific arguments (Berland & Reiser, 2009, 2011; McNeill, 2009; McNeill, Lizotte, Krajcik, & Marx, 2006). We build on this prior work with practices related to modeling by adding the notion of models as explanations of phenomena that we can then apply in multiple contexts. Our instructional approach stresses the goal of representing, comparing, evaluating, and reaching consensus on explanations of phenomena as models. We also emphasize the usefulness of constructing explicit external representations of models (such as diagrams of force and motion, food webs, atomic and molecular structure, and so on).

This emphasis within scientific modeling has implications for the choice of topics that can be investigated with modeling practices. Some scientific topics are more suitable than others for making explanatory components and non-visible mechanisms of phenomena visible at a level consistent with grade-level state benchmarks and standards. Although a phenomenon may be observed and empirically investigated, it may be difficult to help students construct mechanistic understandings of that phenomenon from the evidence. For example, a unit on the function of plant parts that asks students to identify those parts and their general function, if redesigned to incorporate modeling practice, would need to model the non-visible components and mechanisms of plant growth. Such a redesign would be difficult as it would require helping younger students understand photosynthesis at the molecular level without building on a particle model of matter.

Therefore, we have focused on science topics for which students can construct and revise diagrammatic models of non-visible explanatory components over time. For middle school, we used units under development as part of the Investigating and Questioning our World through Science and Technology project (IQWST; Krajcik, McNeill, & Reiser, 2008; Shwartz, Weizman, Fortus, Krajcik, & Reiser, 2008). We embedded more explicit supports for modeling in two sixth grade IQWST units. Both units target explanatory models with non-visible components that describe processes occurring over time: a physics unit on light in which students model light rays travelling through space and their interaction with materials, and a chemistry unit about the nature of matter in which students model particles of gas and their movement. We have also extended this curriculum approach to an eighth grade unit on natural selection in which students develop evidence-based explanations of population change. They begin with two individual cases of natural selection, finches in the Galapagos Islands and peppered moths in the United Kingdom. The students then adapt their explanations of natural selection to construct a more general model that accounts for population change through differential survival in a population containing natural variation. We also created an elementary fifth grade unit on evaporation and condensation that introduces the notion of particles and their movement without addressing the full molecular model presented in the IQWST sixth grade unit (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011). The fifth grade unit enabled us to consider the foundations of a more sophisticated model of matter developed in the sixth grade unit.

Deciding how to bring modeling practice into classrooms through curriculum materials. The lack of agreement among school districts and states about which science topics should be taught each year prevented us from developing new units for the multiple school districts in Illinois, Ohio, and Michigan that partnered with us. Thus, in addition to developing a modeling-focused unit on evaporation and condensation, we also developed a set of principles to help teachers embed the practice of scientific modeling in suitable existing curriculum units (Kenyon, Schwarz, & Hug, 2008). We worked with teachers to use these principles to modify commercially published and district-authored units. The topics of these units included form and function in the human body and the properties of electrical circuits.

Identifying elements of modeling practice to target. As described earlier, we selected constructing, using, evaluating, and revising models as the central elements of modeling practice. However, there are many potential approaches to engagement with these elements. We focused on contexts that emphasize comparative evaluation of models, leading to their revision, in order to highlight the nature of models as explanatory tools that can be improved with new evidence, rather than as "final form" answers to scientific questions. Therefore we developed problem contexts requiring iterative model construction and revision through metamodeling discussions as well as social contexts such as peer evaluation and consensus model-building (Kenyon et al., 2008; Schwarz et al., 2009). As the problem and social contexts were enacted somewhat differently for the various curricular materials and classrooms, there was likely an influence on the learning opportunities and engagement in scientific modeling. For example, some materials (and the teachers using them) engaged students in comparing and contrasting representations and their meanings in diagrammatic models, while others emphasized consistency with empirical evidence. Some approaches emphasized metamodeling discussions and language, while others primarily emphasized the construction and revision of models. Each context and approach affected outcomes that guided revisions of our learning progression.

Challenges in Supporting Teachers' Instruction of Scientific Modeling

An important set of challenges in empirical investigations of a learning progression for a practice arises when helping teachers to better understand the practice and incorporate it into their teaching. Most teachers perceive that the goals of science teaching, reinforced by the pressure of high-stakes assessment, require a focus on science content. These perceptions manifest themselves in several forms, sometimes reducing opportunities for engaging in the full range of targeted elements of modeling practice. Yet if students do not have adequate opportunities to engage in modeling, we have little evidence for evaluating and revising the construct maps that comprise our learning progression.

Viewing practice and content as competing goals. One instructional challenge emerged in the teachers' approach to the relationship between scientific practices and content. While we, as researchers and curriculum designers, see engaging in modeling practice as an effective way to develop deeper explanations of scientific phenomena (i.e., content), teachers may think scientific practices and scientific content represent separate and competing goals. Or teachers may lack the pedagogical strategies that can support students in using scientific practices to develop scientific ideas. Most teachers have never used models and modeling other than in a demonstration of a correct scientific idea (Justi & van Driel, 2005; Schwarz et al., 2009; van Driel & Verloop, 1999; Windschitl et al., 2008). Thus viewing modeling as a process that involves constructing, using, evaluating, and revising models as tools for advancing students' thinking may be counter to typical school, curriculum, and teacher norms. In our initial curriculum enactments, we found that some teachers involved in teaching the MoDeLS curriculum materials focused on the use of models to convey scientific content to their students. This focus was at the expense of engaging students more fully in the practice of modeling through repeated opportunities to work with partially correct models and to compare, evaluate and revise them.

Integrating metaknowledge into support of the practice. Another challenge for science instruction incorporating scientific practices arises in the integration of metaknowledge. This challenge stems from the tension between an integrated strand model of science literacy (NRC, 2007, 2009), in which practices are viewed as vehicles for the development and use of scientific knowledge, and the idea that process, content, and the nature of science are separate learning goals. Some teachers had difficulty incorporating the metamodeling aspect of the practice, particularly at appropriate and critical points in the curriculum, since this aspect added another layer of complexity. Other teachers ignored the metaknowledge aspect of modeling or used it as additional information to be learned (e.g., the definition of a model). Not surprisingly, it was also challenging for teachers to develop pedagogical strategies for both elements of the practice and the associated metamodeling knowledge – particularly in their first use of the materials. For example, asking students to engage in discussions that compare models to better understand important criteria for evaluation and using those discussions for improving models were not straightforward endeavors. Social and school norms (e.g., giving the teacher the correct answer or favoring the model presented by a more likable classmate) conflicted with the norms of the scientific practice. These conflicts posed difficulties for highlighting metamodeling knowledge that should guide performance of the elements of the practice, such as the consistency of the model with empirical evidence or the utility of a model in explaining and predicting phenomena. These difficulties influenced students' learning outcomes with respect to the learning progression. For example, if the teacher and school norms promote using models to "show the correct science answer," then a learner might have more difficulty exhibiting the higher levels of reflective practice in the generative construct map that include the idea that models can be tools for thinking about the world.

Supporting teachers through professional development and curriculum design. To address these challenges, we focused our professional development and curriculum design efforts on achieving a more seamless integration of the metaknowledge guiding the elements of modeling practice with the practice of constructing and using models to explain phenomena. We studied our curriculum approach in several different classroom settings, provided teachers with professional development, and modified the curriculum materials for use in additional classrooms. Some of our enactments were with teachers who followed an entire modeling unit; other enactments were with teachers who integrated modeling activities into their existing classroom curricula and engaged students in modeling practices in several contexts. Teachers who engaged their students in modeling practice over several units, and sometimes over multiple years, with project support, reported finding a more productive balance between content and reflective practice in their pedagogical strategies. In addition, teachers' feedback and our analysis of their enactments provided information for use in modifying the curriculum materials. As a result, we revised the elementary materials to support teachers and learners in more effectively relating empirical evidence to model revision, in clarifying the generative purpose of models, and in choosing more effective evaluation criteria and structures to support productive social norms for peer model evaluation. We modified the middle school materials to streamline the metamodeling discussions that may have been overwhelming to some teachers. We are currently studying teacher enactment and changes in student's modeling practice to determine how teacher-student interactions may have affected student-learning outcomes.

Challenges in Obtaining Evidence of Students' Reflective Practice

Designing appropriate written assessments and interview protocols that can be compared across grade levels and topics to inform redesign of the learning progression has revealed other research challenges: how to assess reflective practice that involves both engagement in the practice and understanding of the practice; how to provide scaffolding in assessments; and how to tease apart content learning gains from improved sophistication in the practice.

Analyzing modeling performance and metaknowledge in assessments. We developed our learning progression with a commitment to the integration of metamodeling knowledge with the elements of the practice (Kenyon et al., 2008; Schwarz et al., 2009). The target is reflective practice in which learners engage in the practice with understanding, not simply as a routine. For example, teachers and curriculum resources should help students see the need for labeling from the perspective of the audience that is trying to understand the phenomena, rather than stressing the importance of labeling diagrams and encouraging students to label their models, essentially as an end in itself. Thus, by itself, increased labeling is not necessarily evidence of reflective practice. We did not want to teach and then assess only the performance of aspects of the practice (with little rationale) or only metamodeling knowledge (with no engagement in the practice). Our construct maps focused not only on students' actions (such as labeling) but also on their rationales for choosing particular actions.

In order to assess both students' performances of modeling practice and their rationales for these performances, we wanted to observe their spontaneous justifications for modeling tasks. We also wanted to observe whether they answered questions about metaknowledge in terms of their specific decisions in performing the practice. Thus we used questions in both written assessments and interviews that varied in their focus on the performance of elements of the practice, on metamodeling knowledge, and on the connection between the two as vehicles to analyze the connection between the performance of elements of the practice and metaknowledge. For example, we developed tasks that asked students to perform an element of modeling practice, such as making a prediction using a model: "Use your model [of evaporation] to predict what will happen when a marker dries out." We asked other questions that focused on metaknowledge, such as "How are models useful?" For both types of assessment item, we looked for evidence of metaknowledge as applied to engaging in the practice according to our construct maps (Table 1, Appendix). The metaknowledge questions were sometimes useful in eliciting students' ideas that they rarely mentioned when working on modeling tasks (such as definitions of models). In general, however, we found that the questions that addressed both performance and knowledge of modeling practice were the richest ones for generating examples of student reflective practice. Thus most tasks explicitly required practice with metaknowledge as justification (e.g., "construct a model to explain this phenomenon, and discuss how it is useful for explaining what is going on.")

One approach that merges practice and metaknowledge is *grounded assessment* – interviews or written assessments that are contextualized in students' classroom work. For example, after students had revised their models of the movement of odors in a room based on experiments with air, we asked them how their revised models differed from their previous models and why the revised models were better. Contextualized questions such as these can be more productive in eliciting students' ideas than more abstract questions such as "why do you (or why does a scientist) revise models?" Students can draw on their experiences to justify why their revised models are better. Our scoring requires the integration of performance and metaknowledge – students who understand the movement of the particles and can build a better model but lack a sophisticated understanding of why their new model is better (other than "it's more correct") are distinguishable from students who can connect their modeling decisions to the importance of features such as the generality of the model, its utility in making new predictions, or the presence of a more complete causal mechanism.

Providing varying degrees of scaffolding in assessments. Another important challenge in designing written items or interview questions is how much scaffolding should be provided to support students' responses. Even in grounded assessments, students may not justify their decisions explicitly without prompting. Indeed, it may be challenging for students to give rationales for their performance of elements of modeling practice even when directly questioned in interviews. Students are much more familiar with questions targeting particular scientific content knowledge than with questions asking for a rationale for their decisions about a scientific practice. Interview questions about what the students considered in the construction of their models may not elicit all their construction decisions. Because our learning progression is about reflective practice, which comprises both doing and understanding modeling practice, information about only one of these aspects is insufficient to firmly locate students' at particular levels.

However, specific prompting about decision rationales has disadvantages as well. For example, following an open-ended interview question with the question "Did you use any of the information from the scientific experiments in constructing the model and if so, how?" prompts students to think about the relationship between the model and the empirical data, even if that consideration was not part of their original decision-making. Thus there are trade-offs between the more open-ended question (with a wider range of possible responses) and the more targeted question that may over-represent what students thought about in performing the practice. The best strategy is to attempt to triangulate across students' responses to written assessments and reflective grounded interviews, the rationales they provide in classroom discourse, and improvements that appear in their modeling work over time (Baek & Schwarz, 2011; Zhan, Baek, Chen, & Schwarz, 2011).

Teasing apart content and practice. A central challenge in assessment design for a scientific practice concerns the relationship between content and practice. There are several key issues here. First, it is important to differentiate improvement in the substance of students' models from more general improvement in modeling practice. For example, as students learn more about the particle nature of matter, they shift from representing matter as continuous to representing matter as particles with empty space between them (Smith et al., 2006; Stevens, Delgado, & Krajcik, 2010). These models are indeed more sophisticated and reflect important learning. However, improvements in the model may not be linked to improvements in the modeling practice; rather, students may have learned more about what matter is made of. Thus it is important to distinguish learning about specific scientific explanations, such as learning about the particulate nature of matter, from learning something more general about modeling practice, such as the importance of representing process and mechanism in a model.

Second, it is possible that limitations in proficiency with the scientific content may lead to under-representation of students' growth in modeling. For example, perhaps students have clear ideas about the importance of providing a mechanism that accounts for changes over time, but they do not understand a particular phenomenon well enough to speculate on a mechanism that could explain their observations. This is a more difficult problem. One strategy is to code for the presence of a mechanism in students' models independently of whether there are scientific inaccuracies. However, this is only a partial solution because lack of candidate explanatory concepts and lack of confidence in their explanations may keep students from speculations about a mechanism in their models.

Our construct maps attempt to address these issues by looking for improved performance guided by appropriate rationales. Students should advance beyond saying "our new model is better because it has particles" to justifying how a model of particulate matter fits the evidence better. Thus, if the growth we uncover is apparent, not only in the substance of the model but also in the rationales students provide, we can attribute these improvements to increased understanding of modeling.

The use of grounded interview and assessment questions helps tease out which model improvements seem linked to improvements in the reflective practice of modeling. For example, many elementary students move from literally depicting an open container that lost water through evaporation to representing small, invisible particles of water moving into the air (Baek et al., 2011). When this improvement in modeling is accompanied by changes in students' views of what models do, there is evidence for more than simply a gain in content knowledge. For example, compare these two rationales (from two fifth grade students' post-unit interviews about models). One student commented that "a model would [be] like an actual Coke can with water on the side, or a picture of it, that is more detailed and colored …" In contrast, the second student's response is more representative of those after the modeling unit since it focuses on the explanatory power of the model: "because it just doesn't show a picture or a diagram. … It doesn't just show it, it explains." The second student appears to consider different criteria for what a model needs to do and offers these criteria as rationales for how the new model is an improvement. The grounded questions allow us to avoid students' unfamiliarity with new content or the challenges of decontextualized questions that might not fully reveal what they can do. However, this strategy does not solve the problem of students' answers on pretests that under-represent their knowledge about modeling if their unfamiliarity with content keeps them from speculating on possible explanatory mechanisms.

Another strategy we have explored is "neutral context" questions that are set in contexts outside the topic of study. For example, we asked students to describe the strengths and limitations of several models a scientist uses to explain what a plant needs to grow. These questions, combined with the other measures, allow us to distinguish learning about content from learning about the practice. If students can more effectively critique models of plant growth after a modeling unit on unrelated science content, such as light or the nature of matter, this improvement appears due to what they have learned about developing and evaluating models.

CHALLENGES IN ANALYZING STUDENTS' WORK AS THEY ENGAGE IN MODELING PRACTICE TO REVISE THE LEARNING PROGRESSION

We are using findings from classroom enactments to test and revise our initial learning progression. We have attempted to triangulate findings from analyses of written assessments, student interviews, classroom artifacts, and classroom conversations to assess students' level of modeling practice and to examine whether and how this level improves with more experience with the practice. Our analyses revealed some limitations in our original construct maps arising from our attempt to use only two dimensions to characterize modeling practice. In this section, we describe the challenges that emerged in our attempts to use the learning progression to analyze students' work as they engage in modeling practice. We also discuss the strategies we used to revise the construct maps that comprise the learning progression in response to these analyses.

Challenges in Analyzing Students' Work as They Engage in Modeling Practice

Students' work matching indicators from different levels. Students' work as they engaged in modeling practice sometimes appeared to be situated across levels, matching indicators from both levels. For example, we found that some students' work matched at least one Level 2 descriptor since these students constructed and used models that included non-observable processes, mechanisms, or components (one aspect of Level 2 in the generative construct map). Yet some of the same students appeared to consider the model's purpose as a veridical illustration of phenomena (e.g., including particles that can only be seen with a powerful microscope), an indicator at Level 1. We found other difficulties in aligning indicators across levels. For some students who used non-observable processes or mechanisms in their models (Level 2), the use of evidence to support their models was not explicit in either their models or their associated rationales, which is an important factor in distinguishing between Levels 2 and 3 of the generative construct map.

In general, the level of students' responses to modeling tasks and accompanying rationales sometimes varied, depending upon the indicator considered – the source of the evidence (authority or empirical evidence), the nature of the explanation (description, a vague sense of explanation, or a more precise sense of process and mechanism), or the generality (versus literalness) of the model. Individual student responses in assessments and interviews did not always provide enough information to allow us to distinguish between levels across these indicators. Their responses sometimes matched different levels for different indicators. Thus it was difficult to decide where to locate students' work as they engaged in modeling practice and to identify the key aspects of each level. This difficulty suggests that we combined too many indicators in each construct map. We conclude that different aspects of understanding within the same dimension should be teased apart to better analyze students' modeling practice.

Practice and metaknowledge not always evident together. Students' work as they engaged in modeling practice sometimes included only elements of practice or only elements of metaknowledge, but not both. For example, Level 1 student models occasionally included literal components as well as some non-visible components or processes. If the students provided no rationale for the inclusion of various components and there was no follow-up to augment the item or interview prompt, it was difficult to distinguish between Levels 1 and 2. These cases reinforce the importance of including probes to reveal the reasoning that underlies students' actions and the importance of not relying only on the substance of students' models to ascertain their level of proficiency with the practice.

Ambiguity in language of students' justifications. Sometimes there was ambiguity in students' language (such as in their use of the words "explain" and "detail"). This ambiguity makes it difficult to interpret students' work as they engage in modeling practice since the meaning of these words varies widely across contexts and over time. Many students discussed how they developed their model to "explain." However, "explain" sometimes meant illustrate and at other times meant provide a mechanism. For example, when one fifth grade student was asked after instruction, "Would you call this [example drawing] a model?" he responded: "Because it does explain something in its own way. … It explains like solids, liquids and gas. It explains the key. It explains what's happening to the strawberry banana orange juice." This response demonstrates how the meaning of "explaining" ranged from "illustrating" (the model depicts particular components like solids, liquids, and gases; the model includes a key) to "depicting what is happening" – a Level 2 response. In other cases, students use "explaining" to mean showing a process or mechanism, contrasted with simply "showing something." Similarly, for some students, the words "more detail" at first meant simply providing more information, but later meant more relevant detail that was useful in explaining.

Such ambiguity in students' language about their practice is not surprising. Part of engaging in a practice involves developing particular norms, expectations, and ways of behaving, all of which require specialized use of language. In science, this specialized language overlaps with everyday language, for example, in the use of words such as "evidence," "explain," "argue," "know," and so on. However, these words begin to acquire more specialized and nuanced meanings as students engage more deeply in particular scientific practices. Thus analyzing students' reflective practice requires going beyond the use of particular words (such as "explain" versus "show") and analyzing their work for evidence of particular shades of meaning.

Variation in the extent to which questions encouraged more sophisticated practice. Students' work as they engaged in modeling practice seemed influenced by the opportunities for reflective practice in the assessment items. Some questions and activities explicitly required students to apply their models in new contexts, an important characteristic of Level 3. However, even if students successfully applied their models to these new contexts, it was not always clear whether they fully understood the role of models as tools for generating thinking. Additionally, when students used more general components, as well as relationships between components in the model, in their applications to new contexts, it was not clear that they understood that the model provided more power to explain additional aspects of a phenomenon. We also found some curricular materials gave students the opportunity to consider alternative and multiple representations for modeling components while other materials did not. As a result, there were limited opportunities to engage in modeling practice at Level 3 through classroom artifacts and conversations. These findings suggested the importance of triangulating interpretations of student performance across a range of tasks that include sufficient opportunity to engage in the more sophisticated aspects of the practice and probing to examine students' rationales for making potentially more sophisticated decisions.

Revising the Learning Progression to Address These Challenges

One particularly salient challenge is that students' work as they engaged in modeling practice included multiple features that were not captured by our initial two construct maps. To address this challenge, we continued to unpack the construct maps to describe several subdimensions of student work. We extracted the primary features that seemed to distinguish between levels of student performance and used them as subdimensions for both construct maps. These subdimensions included prevalent themes in students' work as they engaged in modeling practice, such as attention to audience or to evidence. We created four subdimensions that fit both the generative and dynamic construct maps. Our addition of the subdimensions addressed some challenges in analyzing students' work that included multiple features. In order to revise the construct maps and determine the important subdimensions, we looked for exemplar student work for each subdimension. This search allowed us to revise and clarify categories and levels. In this section, we illustrate the motivation for and the nature of these new subdimensions by focusing on Levels 2 and 3 of our revised generative construct map. The summary descriptions of each level from the original construct map (Table 1) are shown in Table 2, followed by their unpacking through four subdimensions.

Table 2. Four Subdimensions of Levels 2 and 3 of the Generative Construct Map.

	Level 2	*Level 3*
Original Description of Level	Students *construct and use a model to illustrate and explain how a phenomenon occurs*, consistent with the evidence about the phenomenon. Students view models as *means of communicating their understanding of a phenomenon* rather than as tools to support their own thinking.	Students *construct and use multiple models to explain and predict additional aspects of a group of related phenomena*. Students view models as tools that can support their thinking about existing and new phenomena. Students consider alternatives in constructing models based on analyses of the *different advantages and weaknesses* for explaining and predicting these alternative models possess.
Underlying Subdimensions	*Students construct and use models…*	
A. Attention to the model's level of abstraction: i. Literalness vs. salience ii. Specificity vs. generality	i. …as a means to show things that are inaccessible to their senses because of scale differences. ii. …to apply the model to new cases, without making the model applicable to a range of phenomena.	i. …by combining components from more than one model. ii. …to make the model applicable to a range of phenomena.
B. Attention to audience and clarity of communication	…considering how well the model reflects the model creator's thinking or how well the model can be understood by others (no attention to the specific type of understanding).	…considering how well the model communicates ideas of evidence and mechanisms to others.
C. Attention to evidence or authority	….drawing support from learned content knowledge, authority, or empirical evidence.	….drawing support from empirical evidence, with justification for how the evidence supports particular claims about the model's fit with the phenomena.
D. Nature of relationship between model and phenomena	…based on a vague sense of explaining or predicting, without specific attention to capturing process or mechanism.	…attempting to represent mechanism or process to explain and predict phenomena.

Attention to the model's level of abstraction. The first subdimension evident in students' work concerned the issue of literal similarity versus generalization of the phenomena. In other words, students moved from viewing models as literal depictions to understanding the importance of showing what is important, even if these aspects are not apparent. As an example of the latter, during instruction a fifth grade student was asked about his model of the interaction between light and matter:

Interviewer: What makes something a model?

Student: I think it's a model if it has the real stuff. Like it's not fake. It needs to be accurate. It needs to show what's happening. Like this here - it's showing that all four criteria are met to see [a light source, a detector of light, an object to reflect the light, and an unbroken path]. And it could be a replica of it. So this is a replica of seeing.

Interviewer: What do you mean by replica?

Student: A scaled-down model. Smaller. Or even see stuff that you can't.

Here the student refers to the criteria that the class decided were important for seeing an object. The student goes beyond viewing models as literal depictions, and refers (indirectly) to what models need to show ("the four criteria met to see"). The student also indicates models can be "a scaled-down" version used to "see stuff that you can't [see]."

We have also seen developing attention to generality in students' understanding that models should apply to new cases. In the following example, a fifth grade student during instruction suggested removing a particular feature in the evaporation model (a light) and replacing it with something more general (because objects other than a light source can produce heat):

Interviewer: Are there any changes you could make to your model (of evaporation) to make it better? … What kind?

Student: Remove the light and add an explanation because anything can produce heat.

Attention to audience and clarity of communication. A second subdimension that emerged in students' work is attention to audience and to the clarity of communication. This dimension reflects how students attend to potential audiences for their models and to how well the model communicates to those audiences. At Level 2, this dimension includes students' consideration of how well the model reflects the model creator's thinking or how well the model can be understood. At Level 3 the students consider more specific criteria for helping others understand, namely communicating evidence and mechanisms. For instance, a sixth grade student during instruction stated: "I would use my model to explain my ideas…. Well, I do use my model to explain my ideas because it's something I created that I think how I, in my opinion, would think that something might look." This response reflects Level 2 on the audience subdimension, showing that the student sees that the purpose of the model is to reflect her thinking. Similarly, a fifth grade student during instruction commented that scientists "use models to help them figure out something or help other people understand it." After the evaporation/condensation modeling unit, another fifth grade student referred to her use of the model, in a more sophisticated Level 3 fashion, as communicating a mechanism (the speed of the moving particles) that explains phase change:

Interviewer: What were you doing when you were using your model? How did you use your model in class?

Student: Um, well, I used it to explain evaporation.

Interviewer: OK. How did you use it to talk to your group members about it?

Student: Um, well, I showed the molecules and pointed out how they weren't moving as fast as these ones.

Attention to evidence or authority. A third subdimension observed in students' work relates to the nature of support students used to construct their models. This support included prior knowledge, observational or empirical evidence, and authoritative sources such as a reading or the teacher. As an example of Level 2 of this subdimension, a fifth grade student after instruction described how he constructed the model based on the experiments conducted in class during the evaporation/condensation modeling unit:

Interviewer: Did you include any of the evidence of the experiments in any of those models?

Student: …Condensation, I think … we did, because we had evidence because it did collect onto the bottle from the air because it's in a sealed type thing where it had only air. It was just a cold bottle.

Students often did not prioritize empirical evidence, apparently viewing information from books and teachers as on par with empirical evidence. For example, a sixth grade student stated during the unit: "After you get the information, then you can make the model… The information that comes from the book or whatever you learn about."

Some students were able to provide more advanced (Level 3) rationales related to this subdimension, including justifying why empirical evidence supported constructions of or revisions to a model. For example, after the unit, a fifth grade student justified his model changes by referring to an experiment with hot and cold water in which the class discovered that both hot and cold water evaporated, but that hot water evaporated more quickly:

Interviewer: What made you decide to do those changes?

Student: Because we did a few experiments like that hot and cold water one. For the hot and cold water I saw that even after that it was still evaporating. So then when I looked back to that one I knew it was wrong. So for the next one I drew the water evaporating the whole time.

This subdimension presents challenges for students learning the practice of scientific modeling. While this scientific practice prioritizes the use of evidence to build knowledge over authoritative sources that provide answers, this privileging of evidence is unfamiliar to students. Thus it is not surprising to find that students lump evidence with information from teachers and textbooks. Students in traditional science classrooms are more accustomed to reporting *what* they know (i.e., the answers) than *how* they know it (i.e., the justifications) (Berland & Reiser, 2011; McNeill et al., 2006).

Nature of the relationship between models and phenomena. We have also observed students reflect on the relationship between their models and phenomena, as well as on the explanatory nature of their models. This is reflected in the fourth subdimension. At Level 2, students highlight the purpose of a model as an explanation of something about a phenomenon but with an unarticulated sense of what it means to explain. For instance, during a focus group interview, a student toward the end of the IQWST sixth grade chemistry unit stated: “Using a model, you can explain something that’s going on, like we did with the air. We made models of what’s going on in the air.” At other times, students at Level 2 on this subdimension were more specific about the relationship between the components of the model. The following exchange occurred in an interview during the IQWST sixth grade physics unit:

> **Interviewer:** Can you tell me a little bit about the drawing that you made here [the student’s light model]?
>
> **Student**: Well it is showing, it's explaining everything that light can do. Here it's reflecting, here it's transmitting, and later it absorbs. Here it is reflecting off a tree, and this person standing here can actually see it because the light is entering her eyes. Over here it shows shadowing because light is being blocked there.

We coded responses as Level 3 when students incorporated a mechanism into their models that made explicit how the relationships between model components led to the observed phenomena. In the next example, in a class that had just begun to identify empty space (which they called “nothing”) as important, a student in the IQWST sixth grade chemistry unit justified the importance of empty space between particles in a model of odors traveling through air:

> **Teacher** [pointing to the space between particles in the model on the whiteboard]: Nothing! So why is nothing [empty space] there, in the middle of the molecules, able to help me realize why the particles can be compressed, how there’s nothing there? [Student]?
>
> **Student**: Because since there’s *nothing* there [it] can show like the spaces in-between the particles. And when they’re compressed, they go together, and then there’s like less of that space. But when they expand, they spread apart and there’s more of the “nothing.”

There are several challenges in analyzing students’ work as they engage in modeling practice with respect to the model-phenomena relationship depicted.

While sometimes it is feasible to distinguish between models constructed using a vague sense of "explaining something" (Level 2) and models involving more precise explanations through inclusion of components representing processes or mechanisms (Level 3), the distinction is not always clear. Students' rationales are frequently limited and sometimes ambiguous. For example, students may provide a more sophisticated mechanism or process in their model but give a limited rationale for the use of the correspondingly sophisticated model-phenomenon relationship. As in other cases, it is important not to assume that the improved model means a more sophisticated understanding of the practice.

Future work with the subdimensions. We continue to try to better understand how to clarify the different subdimensions as we analyze students' modeling work with respect to these subdimensions. We also continue to analyze the role of content (for example, explanatory components in some science topics might make it easier for students to improve in the model-phenomena relationship subdimension) and scaffolding (probing for adequate rationales) in students' work. Thus we are exploring students' work as they engage in modeling practice across assessment measures (written assessment items, interviews, class talk) in different contexts (different science topics and levels of scaffolding). Finally, the distinction between levels (such as that between Levels 2 and 3) remains relatively coarse. We continue to work on determining how to trace shifts in students' practice within a particular level as well as across levels by conducting finer-grained analyses of students' engagement in modeling practice. We are also examining the empirical relationships between these four subdimensions. We continue to test the subdimensions of the construct maps against the data from classroom enactments.

Overall, the subdimensions present a more detailed consideration of the reflective practice than that represented in our initial construct maps. The subdimensions are important for capturing changes in students' reflective practice. While there are still many challenges with evaluating students' work as they engage in modeling practice, this finer-grained framework allows us to determine how to provide better support for learners through the design of more effective curriculum materials and instruction.

SUMMARY OF CHALLENGES IN DEFINING A LEARNING PROGRESSION FOR A SCIENTIFIC PRACTICE AND IMPLICATIONS FOR FUTURE WORK

In this section, we summarize the challenges we have faced and the implications for learning progression research on scientific practices, as well as more general implications. Within the challenges and implications, we discuss two clusters of related issues – (a) analyzing a practice that combines performance and metaknowledge and (b) the design research nature of learning progression research.

Supporting and Assessing Reflective Practice

Theoretical and methodological challenges arise when developing a learning progression for a scientific practice. A particular challenge arises in the commitment to developing a learning progression for reflective practice – the integration of the performance of elements of the practice with underlying metaknowledge. We assess the combination of students' performance of elements of modeling practice and metamodeling knowledge so as to avoid teaching and assessing routine procedures on the one hand and decontextualized understandings about the nature of science on the other hand. However, the focus, breadth, and number of elements in our construct maps make the associated tools for analyzing student work more complex. We have outlined several difficulties in analyzing gains students make in the practice. It is not convincing to rely solely on students' general articulations of metaknowledge in response to surveys or interviews that focus on general epistemological and nature of science questions. Instead, we look for performance accompanied by indicators of related understanding as reflected in our construct maps (Tables 1 and 2, Appendix). We try to guard against unduly crediting some types of improved student modeling work as indicating improvement in reflective practice. We do not want to interpret improved rote performance as improvement in reflective practice. Nor do we want to assume improved model substance necessarily indicates increased understanding about the practice. We also deal with challenges related to the opportunities for students to engage in reflective practice in current classroom contexts.

Distinguishing reflective practice from rote performance. Our goal is to support and evaluate science as reflective practice. Thus we analyze metamodeling knowledge as used in performance of modeling practice. This analysis requires investigating how students construct, use, evaluate, and revise models in particular content domains. We have described several cases where we attempt to avoid crediting students with improved reflective practice if they show improvement in performance of the practice without understanding. One example is teachers' repeated instructions to students about labeling their diagrams in particular ways. Thus students' labels – without accompanying justification – would not receive credit with respect to our construct maps. In addition to the labels, we also look for students' comments about how labels clarify important components of the mechanism or how labels help the audience construct a chain of cause and effect.

Distinguishing improvements in practice from increased content knowledge. Similarly, we attempt to distinguish improvement in the substance of the model from more general understanding of the practice. For example, as students move from viewing air as continuous matter to viewing it as consisting of particles, they reflect this change in their models. The new models clearly show improvement in their ability to account for phenomena. A student's model might explain that an odor spreads across a room because the odor particles collide with air particles and eventually spread (diffuse) across the room. However, this model does not necessarily mean students have developed more sophisticated ideas about the importance of including mechanisms in their models. We also want to see students justify that the new model represents an improvement because it explains, in a step-by-step fashion, what happens to the odor. One strategy for addressing this issue is to use neutral content assessment items where the modeling task is embedded in scientific phenomena that are not the content focus of the modeling unit.

The opposite interpretation problem may also occur. Because of the link between content knowledge and students' modeling practices, we may underestimate students' proficiency with the latter. It is possible that unfamiliarity with the target domain makes students hesitant to speculate on possible mechanisms even though they may realize that mechanistic explanations are a goal of modeling. A partial response to the problem is to code the scientific accuracy of students' mechanisms separately from whether they attempt to include a mechanism in their model and whether they can describe the importance of the mechanism. However, the possibility remains that students may hesitate to speculate if they lack confidence in their knowledge of the domain.

Tension between the scientific practice and prevalent classroom norms. Scientific practices entail a system of norms, expectations, and ways of acting that may conflict with classroom and school norms. Many researchers have written about the need to move from structuring classrooms in which students are consumers of knowledge provided by authority to structuring classrooms in which students are members of a community of learners who build, evaluate, and refine knowledge according to the practices of an intellectual community (e.g., Bielaczyc & Collins, 1999; Brown & Campione, 1994; Driver, Newton, & Osborne, 2000; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999). Challenges arise when encouraging learners to engage in scientific practices that require that they constructively argue with peers, take the role of authors of knowledge, and recognize that knowledge is continually refined.

The divergence of scientific practices from traditional classroom practices also creates challenges for analyses of students' work as they engage in modeling practice. First, the emphasis on models as the target of sense-making moves beyond simply predicting or capturing regularities in equations or recounting what happens in a particular scientific phenomenon. Instead, modeling focuses students on developing mechanistic explanations of *how* and *why* something happens. Many reforms call for this type of deep understanding. However, such reforms require a shift in the perspective of learners in terms of what constitutes an answer to a scientific question. Second, our attempt to document reflective practice relies on students' rationales for their decisions. Rather than focusing solely on answers, students need to justify why they made particular decisions while engaging in the practice. Furthermore, documenting students' modeling work relies on the idea that students' engagement in the practice is driven by what makes sense and has value in the community rather than by what they are directed to do by the curriculum and by teachers. Thus the nature of students' attitudes within a scientific practice differs from those within traditional classroom practices in which students view learning science as repeating fixed answers to questions.

Viewing practice as "doing with understanding" (Barron et al., 1998) and as reflecting attitudes and expectations creates challenges for support and assessment. However, a reduction of the practice to simply knowledge or skills would diminish the importance of engaging learners in the meaningful knowledge building in science (NRC, 2007, 2009).

Developing Learning Progressions Is Design Research

A second set of challenges concerns the necessary nature of research to define, investigate, and revise a learning progression. A learning progression can be viewed as a hypothesis (Alonzo & Steedle, 2009; Wilson, 2009). However empirical investigations of a learning progression are not best viewed as "hypothesis testing" in the typical sense of this research approach. Learning progressions are conjectures about the *potential* paths learning can take. The learning progression is a hypothesis about how complex learning goals (e.g., an understanding natural selection or the nature of matter) can be built from constituent understandings. The learning progression presents the important elements of a target idea or practice and identifies productive, intermediate stepping stones that lead to advances in reasoning, upon which more sophisticated versions can be built with appropriate support.

The assumption explicit in work on learning progressions is that multiple pathways are possible in movement toward more sophisticated understandings. Furthermore, a learning progression is not a hypothesis about necessary stages of understanding through which learners inevitably progress. Learning progressions are contingent on (1) learning experiences students encounter and (2) support for making sense of those experiences (Lehrer & Schauble, 2009). The learning progression hypothesis includes the elements of knowledge and practice and descriptions of how these elements can build on one another through productive pathways.

Moreover, part of the work of defining a learning progression involves identifying the particular substance of the learning target. Even if there is agreement (e.g., from national and state standards) that particular scientific ideas, such as evolution or the particle nature of matter, should be taught, the research program must include arguments for which aspects of these ideas are essential. These arguments may draw on empirical findings but may also rely on value-based considerations. Empirical evidence can illuminate which challenges may arise in reaching a particular understanding of an idea and can identify important component ideas that may be implicit in the target idea and, therefore, should be targeted for instruction (Krajcik et al., 2008). However, which understandings should be targeted is not just an empirical question; choices about which aspects of these understandings are important must also be made. For example, should learners construct an understanding of evolution by natural selection in advance of understanding the molecular basis of inheritance? Or is the construct of natural selection only useful if it can be built on understanding the molecular basis of inheritance?[1] Empirical research can identify what is feasible, as well as the potential advantages or disadvantages of particular pathways. But empirical evidence cannot be used alone in arguments when value-based considerations must also be taken into account.

The need for both empirical and value-based considerations is even more apparent in learning progressions for scientific practices. National and state standards are much less explicit about which aspects of scientific practice should be targets of instruction; such standards identify developing and investigating explanations, models, and theories quite broadly. There are many variations of scientific practice that could be proposed as relevant for classrooms. These variations might emphasize different aspects of developing knowledge in science, focusing, for example, on designing investigations, analyzing data, developing arguments, producing explanatory texts, and so on. Within any individual element, such as argumentation, there are multiple ways of defining the element, each emphasizing different criteria, such as logical consistency, empirical evidence, coherence, etc. (Sampson & Clark, 2008).

Thus defining a learning progression for a practice involves more than simply investigating the "best way" to reach the learning goal of a particular scientific practice. Part of the research program should develop research-based arguments for what it means to engage in that scientific practice in the classroom. This work combines attempts to design classroom contexts that support the practice with empirical investigations about what is possible and what challenges arise. The hypotheses investigated necessarily include commitments to what should be learned and initial conjectures about what reasonable stepping stones might look like.

A key challenge in this design work arises because it is not a simple instructional task to change the practices through which learners build knowledge in classrooms. As we have said, there is tension in between what counts as "knowing" something in science and students' expectations about knowledge and authority (Herrenkohl et al., 1999; Hogan & Corey, 2001). Thus we are faced with the study of a practice that differs in important ways from what is currently present in classrooms. Dramatic changes in the way knowledge is built through classroom interactions can only occur incrementally and over time (Lehrer & Schauble, 2006).

The design research nature of work on learning progressions has implications for the nature of theories that can be built in this domain. The theories constructed from studies of learning progressions are arguments, supported by evidence, about possible pathways and their associated challenges. It would be over-interpreting the evidence to argue for a necessary sequence. Furthermore, it is important to contextualize the evaluation of these design research arguments with respect to the assumptions that were made about the learning target. Different conceptualizations (e.g., emphasizing argumentation rather than model building or different approaches to supporting modeling) may reveal different challenges and different pathways for learning.

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NOTE

[1] This is the decision reflected in the American Association for the Advancement of Science (AAAS; 2001, 2007) strand maps.

REFERENCES

Abd-El-Khalick, F., BouJaoude, S., Duschl, R., Lederman, N. G., Mamlok-Naaman, R., Hofstein, . . . Tuan, H.-l. (2004). Inquiry in science education: International perspectives. *Science Education, 88*, 397–419.

Acher, A., Arcà, M., & Sanmartí, N. (2007). Modeling as a teaching learning process for understanding materials: A case study in primary education. *Science Education*, *91,* 398–418.

Alonzo, A. C., & Steedle, J. T. (2009). Developing and assessing a force and motion learning progression. *Science Education, 93*, 389–421.

American Association for the Advancement of Science. (2001, 2007). *Atlas of science literacy,* (Vols. 1–2). Washington, DC: Author.

Baek, H., & Schwarz, C. (2011, April). *How teachers and students make sense of and perform model revision and consensus model construction in two 5th grade classrooms.* Paper presented at the annual meeting of the National Association for Research in Science Teaching, Orlando, FL.

Baek, H., Schwarz, C., Chen, J., Hokayem, H., & Zhan, L. (2011). Engaging elementary students in scientific modeling: The MoDeLS fifth-grade approach and findings. In M. S. Khine & I. M. Saleh (Eds.), *Models and modeling in science education* (Vol. 6, pp. 195–218). Dordrecht, The Netherlands: Springer.

Barron, J. S., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., & Bransford, J. D. (1998). Doing with understanding: Lessons from research on problem- and project-based learning. *Journal of the Learning Sciences, 7*, 271–311.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education, 93*, 26–55.

Berland, L. K., & Reiser, B. J. (2011). Classroom communities' adaptations of the practice of scientific argumentation. *Science Education, 95*, 191–216.

Bielaczyc, K., & Collins, A. (1999). Learning communities in classrooms: A reconceptualization of educational practice. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory* (pp. 269–292). Mahwah, NJ: Lawrence Erlbaum Associates.

Brewer, W. F., Chinn, C. A., & Samarapungavan, A. (1998). Explanation in scientists and children. *Minds and Machines, 8*, 119–136.

Brown, A. L., & Campione, J. C. (1994). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 229–270). Cambridge, MA: MIT Press.

Brown, A. L., & Campione, J. C. (1996). Psychological theory and the design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), *Innovations in learning: New environments for education* (pp. 289–325). Mahwah, NJ: Lawrence Erlbaum Associates.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28*, 235–251.

Clement, J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education, 22*, 1041–1053.

Clement, J. (2008). Student/teacher co-construction of visualizable models in large group discussion. In J. Clement & M. A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 11–22). New York, NY: Springer.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9–13.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*, 287–312.

Edelson, D. C. (2001). Learning-for-use: A framework for integrating content and process learning in the design of inquiry activities. *Journal of Research in Science Teaching, 38*, 355–385.

Edelson, D. C., & Reiser, B. J. (2006). Making authentic practices accessible to learners: Design challenges and strategies. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 335–354). New York, NY: Cambridge University Press.

Fortus, D., Rosenfeld, S., & Shwartz, Y. (2010, March). *High school students' modeling knowledge.* Paper presented at the annual meeting of the National Association for Research in Science Teaching, Philadelphia, PA.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799–822.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education, 22*, 1011–1026.

Herrenkohl, L. R., Palincsar, A. S., DeWater, L. S., & Kawasaki, K. (1999). Developing scientific communities in classrooms: A sociocognitive approach. *Journal of the Learning Sciences, 8*, 451–493.

Hogan, K., & Corey, C. (2001). Viewing classrooms as cultural contexts for fostering scientific literacy. *Anthropology & Education Quarterly, 32*, 214–243.

Justi, R., & van Driel, J. (2005). A case study of the development of a beginning chemistry teacher's knowledge about models and modelling. *Research in Science Education, 35*, 197–219.

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. *Science Education, 94*, 525–551.

Kenyon, L., Schwarz, C., & Hug, B. (2008). The benefits of scientific modeling. *Science and Children, 46*(2), 40–44.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education, 92*, 1–32.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah, NJ: Lawrence Erlbaum Associates.

Lehrer, R., & Schauble, L. (2000). Modeling in mathematics and science. In R. Glaser (Ed.), *Advances in Instructional Psychology: Vol. 5. Educational design and cognitive science* (pp. 101–159). Mahwah, NJ: Erlbaum.

Lehrer, R., & Schauble, L. (2004). Modeling natural variation through distribution. *American Educational Research Journal, 41*, 635–679.

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy: Supporting development in learning in contexts. In W. Damon & R. M. Lerner (Series Eds.) & K. A. Renninger & I. E. Sigel (Volume Eds.), *Handbook of Child Psychology: Vol. 4. Child psychology in practice* (6th ed., pp. 153–196). Hoboken, NJ: John Wiley and Sons.

Lehrer, R., & Schauble, L. (2009). Images of learning, images of progress. *Journal of Research in Science Teaching, 46*, 731–735.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive Development, 23*, 512–529.

Lesh, R., & Doerr, H. M. (2000). Symbolizing, communicating, and mathematizing: Key components of models and modeling. In P. Cobb, E. Yackel, & K. McClain (Eds.), *Symbolizing and communicating in mathematics classrooms: Perspectives on discourse, tools, and instructional design* (pp. 361–383). Mahwah, NJ: Lawrence Erlbaum Associates.

Lesh, R., & Doerr, H. M. (2003). Foundations of a models and modeling perspective on mathematics teaching, learning, and problem solving. In R. Lesh & H. M. Doerr (Eds.), *Beyond constructivism: Models and modeling perspectives on mathematics problem solving, learning, and teaching* (pp. 3–33). Mahwah, NJ: Erlbaum.

Lesh, R., & Lehrer, R. (2003). Models and modeling perspectives on the development of students and teachers. *Mathematical Thinking and Learning, 5*, 109–129.

McNeill, K. L. (2009). Teachers' use of curriculum to support students in writing scientific arguments to explain phenomena. *Science Education, 93*, 233–268.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences, 15*, 153–191.

Mohan, L., Chen, J., & Anderson, C. W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching, 46*, 675–698.

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: The National Academies Press.

National Research Council. (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: The National Academies Press.

Passmore, C. M., & Svoboda, J. (2011). Exploring opportunities for argumentation in modelling classrooms. *International Journal of Science Education*. Advance online publication. doi: 10.1080/09500693.2011.577842

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education, 92*, 499–525.

Sampson, V., & Clark, D. (2008). Assessment of the ways students generate arguments in science education: Current perspectives and recommendations for future directions. *Science Education, 92*, 447–472.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education, 89*, 634–656.

Schwarz, C. V. (2002). Is there a connection? The role of meta-modeling knowledge in learning with models. In P. Bell, R. Stevens, & T. Satwidz (Eds.), *Keeping learning complex: The proceedings of the fifth International Conference of the Learning Sciences (ICLS)*. Mahwah, NJ: Erlbaum. Retrieved from http://schwarz.wiki.educ.msu.edu/file/view/Schwarz_ICLS_metapaper.pdf

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., . . . Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*, 632–654.

Schwarz, C. V., & White, B. Y. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*, 165–205.

Shwartz, Y., Weizman, A., Fortus, D., Krajcik, J., & Reiser, B. (2008). The IQWST experience: Using coherence as a design principle for a middle school science curriculum. *The Elementary School Journal, 109*, 199–219.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. *Cognition and Instruction, 18*, 349–422.

Smith, C. L., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic-molecular theory. *Measurement: Interdisciplinary Research and Perspectives, 4*, 1–98.

Snir, J., Smith, C. L., & Raz, G. (2003). Linking phenomena with competing underlying models: A software tool for introducing students to the particulate nature of matter. *Science Education, 87*, 794–830.

Spitulnik, M. W., Krajcik, J., & Soloway, E. (1999). Construction of models to promote scientific understanding. In W. Feurzeig & N. Roberts (Eds.), *Modeling and simulation in science and mathematics education* (pp. 70–94). New York, NY: Springer-Verlag.

Stevens, S. Y., Delgado, C., & Krajcik, J. S. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 47*, 687–715.

Stewart, J., Cartier, J. L., & Passmore, C. M. (2005). Developing understanding through model-based inquiry. In M. S. Donovan & J. D. Bransford (Eds.), *How students learn: History, mathematics, and science in the classroom* (pp. 515–565). Washington, DC: The National Academies Press.

Tabak, I., & Reiser, B. J. (2008). Software-realized inquiry support for cultivating a disciplinary stance. *Pragmatics and Cognition, 16*, 307–355.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*, 357–368.

van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modelling in science. *International Journal of Science Education, 21*, 1141–1153.

Weiss, I. R., Pasley, J. D., Smith, P. S., Banilower, E. R., & Heck, D. J. (2003). *Looking inside the classroom: A study of K–12 mathematics and science education in the United States*. Retrieved from Horizon Research website: http://www.horizon research.com/insidetheclassroom/reports/looking/complete.pdf

White, B. Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10*, 1–100.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*, 3–118.

Wilson, M. (2005). *Constructing measures: An item response modeling approach*. Mahwah, NJ: Lawrence Erlbaum Associates.

Wilson, M. (2009). Measuring progressions: Assessment structures underlying a learning progression. *Journal of Research in Science Teaching, 46*, 716–730.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*, 941–967.

Zhan, L., Baek, H., Chen, J., & Schwarz, C. (2011, April). *Investigating patterns and rationales for 5th grade students' scientific models*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Orlando, FL.

APPENDIX

A Construct Map for the Dynamic Dimension: Understanding Models as Changeable Entities

Level	*Description of Reflective Practice (Including Performance of Elements of the Practice and Associated Metaknowledge)*
4	*Students consider changes in models to enhance the explanatory power prior to obtaining evidence* supporting these changes. Model changes are considered to develop questions that can then be tested against evidence from the phenomena. Students evaluate competing models to *consider combining aspects of models* that can enhance the overall explanatory and predictive power.
3	*Students revise models in order to better fit evidence that has been obtained and to improve the articulation of a mechanism in the model*. Thus models are revised to improve their explanatory power. Students compare models to *see whether different components or relationships fit evidence more completely and provide a more mechanistic explanation of the phenomena*.
2	*Students revise models based on information from authority (teacher, textbook, peer) rather than evidence gathered from the phenomenon or new explanatory mechanisms*. *Students make modifications to improve detail or clarity or to add new information*, without considering how the explanatory power of the model or its fit with empirical evidence is improved.
1	*Students do not expect models to change with new understandings*. They talk about models in absolute terms of right or wrong answers. Students compare their models by assessing if they are *good or bad replicas of the phenomenon*.

Note. Adapted from "Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners," by C. V. Schwarz, B. Reiser, E. A. Davis, L. Kenyon, A. Acher, D. Fortus, Y. Shwartz, B. Hug, and J. Krajcik, 2009, Journal for Research in Science Teaching, 46, p. 647.