

Designing and Testing the MoDeLS Learning Progression

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Abstract

Modeling is a core component of scientific practice and is a central part of scientific literacy. We define modeling practice as including both the performances and the metaknowledge that guides and motivates the practice. We incorporate the practice and knowledge components into an initial learning progression that is being implemented and tested across elementary and middle school grades. This paper illustrates and provides a rationale for elements of that progression. It also sets the context for the empirical studies testing the progression whose results are presented in the subsequent papers in this paper set.

A Learning Progression for the Scientific Practice of Modeling

Current work in science education has emphasized the importance of engaging learners in scientific practices — social interactions, tools, and language that represent the disciplinary norms of how scientific knowledge is constructed, evaluated, and communicated (Duschl, Schweingruber, & Shouse, 2007). A focus on scientific practices such as inquiry, modeling, or scientific explanations can help learners understand the nature of disciplinary knowledge, and how to develop and use such knowledge (AAAS, 1990, 1993; NRC, 1996). Nonetheless, scientific practices are challenging for both teachers and students. Scientific practices require shifts in classroom norms and activities (e.g. from listening to a teacher provide the correct scientific information, to collecting and interpreting data and connecting patterns in data with theories and explanations). For effective participation in practices, teachers and students need sustained guidance and support with these scientific practices as well as for the scientific ideas addressed by the

practice. Such support may include curriculum materials, teacher education, and professional development (Duschl et al., 2007).

The MoDeLS project, *Modeling Designs for Learning Science*, has begun to develop a learning progression to represent successively more sophisticated understandings and practices of scientific modeling. Modeling is a core component of scientific practice, and plays an increasingly important role in modern science, engineering, and science learning with the prevalence of computational models. Models play an important role in science by mediating empirical evidence and theoretical explanations. A scientific model is an abstract, simplified, representation of a system that makes its central features explicit and visible (Harrison & Treagust, 2000), and can be used to generate explanations and predictions of natural phenomena.

Modeling plays an equally important role in science learning by providing external representations that help learners develop and work with scientific ideas (Lehrer & Schauble, 2000; Stewart, Cartier, & Passmore, 2005; White & Frederiksen, 1998). Engaging in modeling can help learners build subject matter expertise, epistemological understanding, and practices and skills such as systems thinking (Acher, Arcà, & Sanmartí, 2007; Lehrer & Schauble, 2006; Lesh & Doerr, 2000; Schwarz & White, 2005). Working with models can scaffold communication and facilitate classroom discourse by making patterns in data and causal explanations explicit and visible. Furthermore, having the opportunity to engage in scientific modeling plays an important role in developing scientific literacy – helping students explain observable phenomena, predict unobservable phenomena, and make informed personal and societal decisions.

The goal of our MoDeLS work is to develop a learning progression that can be used to design supports for learners. A learning progression specifies how knowledge and practices can be built over time, by articulating successively more sophisticated versions of the knowledge (Duschl et al., 2007; Smith, Wiser, Anderson, & Krajcik, 2006). It articulates a trajectory that learning can follow, building on the understandings learners bring to the classroom. Thus, developing a learning progression for modeling entails:

- articulating and unpacking a version of the target practice appropriate for learners
- identifying the challenges in understanding and participating in the practice

- identifying the relevant prior conceptions and experiences learners bring to the classroom
- identifying possible trajectories through which these ideas can be built

The literature on modeling in science learning has provided a strong foundation on which to understand both the challenges facing learners and the conceptions they bring to the modeling tasks.

Defining Models The Modeling Practice

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 & Lehrer, 2003; Treagust, Chittleborough, & Mamiala, 2002). To reiterate, we define a model as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena. In the framework for modeling presented by Lesh and Doer (2000), a model consists of “elements, relations, operations, and rules governing interactions that are expressed using external notation systems.” The elements are the conceptual elements used to represent important aspects of phenomena. The behavior of the model is determined by the rules and operations governing the model. Models are used to provide illustrations, predictions, and explanations of natural phenomena. This relationship between models and phenomena is shown in Figure 1. In particular, observations about the phenomena can be used to generate candidate ideas about the elements, relations, operations and rules within the model. The model has to fit the data collected about the phenomena. The model can provide an explanation for why the phenomenon behaves in the way it does, and should generate new predictions that can be tested against data from the phenomena.

Models are representations of systems, but it is important to clarify that not all representations are models. Models are specialized representations that embody aspects of mechanism, causality, relationship, or function to explain and predict phenomena. Models can also be contrasted with more general theories, in that models embody only portions of theories for specific purposes. Examples of models include the Bohr model of the atom or the particle model of matter, a light ray model, the water cycle model (including the movement of water from land/oceans and air), and a food web model indicating interactions between organisms.

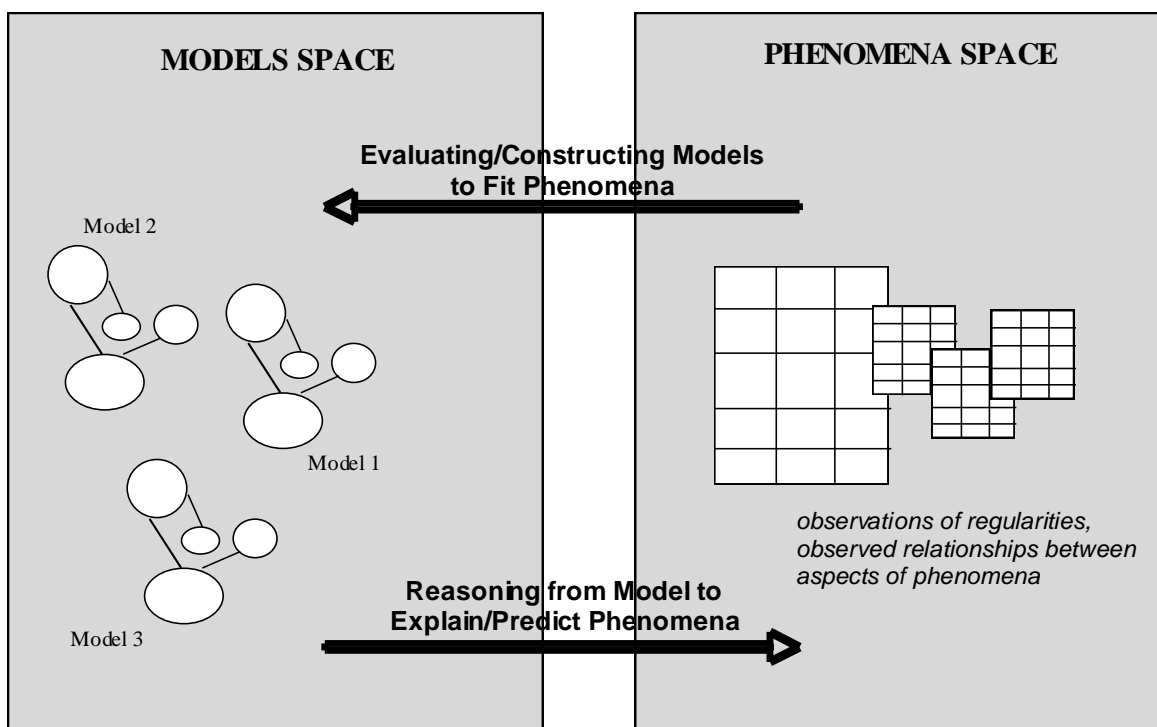


Figure 1. Working with models by reasoning back and forth from implications of the model to characterizing the behavior of the phenomenon.

Models can be further classified into two types: internal models and expressed models (Gobert & Buckley, 2000). Internal models refer to the individuals' internal representation of the explanatory mechanisms and/or predictive patterns and laws that underlie particular natural phenomena. An example of such a model is one's mental conception of matter as consisting of moving particles with empty space in between those particles. Expressed models can be thought of as the external representations of internal models. For example, to explain how phase change occurs for a particular substance, one could draw or build an external representation of matter using ball-and-stick diagrams of atoms and molecules or develop animations of matter using moving dots to represent particles in motion.

To develop a learning progression, we have attempted to tease apart the important aspects of the modeling practice for K-12 learners, and the knowledge that underlies it. Our goal is to reflect aspects of the authentic science practice that would be achievable and feasible to motivate within the context of K-12 science. The first step in crafting the learning progression is to "unpack" the learning goals, drawing out the implicit

understandings they entail (Krajcik, McNeill, & Reiser, 2008), and attempting to organize them into a coherent framework.

There are three important commitments in our learning progression design — the integration of metaknowledge and practice, the integration of sensemaking and communicative aspects of the practice, and the construction of modeling understandings that generalize beyond specific scientific contexts. We describe each of these in the next sections.

Integration of Metamodeling Knowledge and Practice

The first central commitment in our learning progression is the weaving together of engaging in the practice — the performance of aspects of scientific modeling — with the knowledge that underlies it and makes it meaningful. Involving learners in meaningful participation with the practice requires that they understand the rationale and norms that govern the practice (e.g. what are they doing, and why are they doing it). It is therefore important that they acquire an understanding of certain ideas about the roles of models and modeling in science. Such knowledge can also help make the practice purposeful for learners. Furthermore, knowledge about the nature and purpose of models (metamodeling knowledge) is important in its own right as an aspect of scientific literacy. Learners need to understand what models are used for, why they are used, and what their strengths and limitations are, in order to appreciate how science works and the dynamic nature of knowledge that science produces.

Our work on the development of modeling practice takes the stance that the practice and the metaknowledge are more powerful and meaningful when addressed with one another rather than as separate components. The metaknowledge is significantly less meaningful without the accompanying practice to contextualize and specify the knowledge. We see the performance part of the practice itself and the metaknowledge inextricably linked. To treat them as separate learning goals for educational designs would not reflect what it means to be a scientific practice. It would be a poor version of the practice if students were to engage in the steps of the practice by rote rather than understanding the purpose of each step, or strive to achieve models of particular forms without understanding why those characteristics of models are important. Similarly, we would not want to attempt to achieve abstract decontextualized understandings about

science, where students could describe characteristics of the nature or purpose of models, without being able to follow through in modeling practice with the implications of those understandings to guide and constrain the practice. Therefore, our learning progression specifies the aspects of metaknowledge that influence the performance of the practice, and we attempt to support and look for growth in the interaction of metaknowledge and practice.

We define the practice of modeling appropriate for science classrooms as embodying key aspects of a theory and evidence into an expressed representation, using the representation to illustrate, predict and explain, and evaluating and revising the representation as it is used. In particular, we have operationalized the practice of modeling to include four components. These components are based on prior work related to epistemologies and the nature of science (Carey & Smith, 1993), and work on student learning with and about models (Grosslight, Unger, Jay, & Smith, 1991; Snir, Smith, & Raz, 2003; Stewart et al., 2005). We have identified four aspects of modeling practice to target for students:

- Constructing models: Students construct models consistent with prior evidence and theories to explain or predict phenomena.
- Using models to illustrate, explain, and predict phenomena
- Evaluating models: Students compare and evaluate the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena.
- Revising models: Students revise models to increase their explanatory and predictive power, taking into account additional evidence or aspects of a phenomenon

These practices are consistent with design-based practices of (e.g., design, test, and revise, Fortus, Krajcik, Dersheimer, Marx, & Mamlok-Naaman, 2005) and those of mathematical modeling practices (e.g., describe, manipulate, translate, and verify, Lesh & Doerr, 2003).

It is important to point out the central role that constructing models plays in our realization of this scientific practice for students. In considering what aspects of the practice to foreground for students, we felt it crucial to involve learners in the

construction of models, rather than only working with models provided by scientific authorities. There are several arguments for this stance. As others have argued, the pedagogical benefits of working with scientific models rests critically on having students develop models to articulate their understanding of how a scientific phenomena behaves (Acher, Arcà, & Sanmartí, 2007; Schwarz & White, 2005; Stratford, Krajcik, & Soloway, 1998; Wilensky & Reisman, 2006; Windschitl, Thompson, & Braaten, 2008, in press). Furthermore, we hypothesize that the process of revising models that learners themselves have constructed to reflect advances in their understanding is more effective than traditional uses of models in helping the learners understand the need to evaluate models and improve them in light of new findings. Finally, we argue that constructing and evaluating models are the most discrepant part of current use of models in schools, where models such as physical simulations (e.g., a stream table) or computational models or visualizations are used to help students see how phenomena behave, rather than as ongoing attempts to capture and then improve on explanations of phenomena (Schwarz & Gwekwerere, 2007).

We term the knowledge underlying the practice *metamodeling knowledge* (Schwarz & White, 2005). This knowledge includes understanding the purpose of scientific models, their nature, and criteria for evaluating them. We focus on how the underlying knowledge can help guide the practice. Thus we identify epistemological understandings as learning goals that can help students plan and evaluate their investigations. Knowing the forms and purposes of models and criteria for evaluating them can help guide learners in more successful and reflective use of models in scientific reasoning.

As a starting point in describing metamodeling knowledge, we have drawn on standards and reform documents in describing what students would need to know about models (AAAS, 1990, 1993, 2001), and on empirical studies (Schwarz & White, 2005) to characterize the important dimensions of this metamodeling knowledge. First, we aim to help learners understand the purpose of modeling and modeling as powerful tools and practices for advancing our knowledge about the world. In particular, we aim to help learners understand that models can be used to represent scientific phenomena that are too complex or difficult to observe directly and they enable us to predict and explain

natural phenomena. Secondly, models are abstractions, not literal representations. As such, multiple models are possible. Finally, models are evaluated and revised based in empirical evidence and theoretical notions to improve their predictive and explanatory power.

Our initial attempts to develop a progression for metamodeling knowledge uncovered extensive overlaps between these various dimensions of understanding about modeling. As a result, we collapsed our original dimensions into two emphases that concern the generativity and dynamic nature of models. (See figure 2).

- *Models are generative tools for prediction and explanation:* Models need to be both reflective of our understanding, representing the best explanations we can develop, but also are useful to generate new knowledge, by leading to new predictions about phenomena, and drawing out the implications to develop new explanations for aspects of phenomena not yet studied
- *Models are dynamic and are subject to change as our understanding improves:* In other words, models evolve and improve when tested and revised with empirical evidence and theoretical argumentation.

Sensemaking and Communication

Models can be used to help scientists and learners to generate new understandings or to communicate their understandings to others—and often are used for both purposes. These two aspects are related, mutually supportive, and often occur simultaneously. However, one or the other may be foregrounded at a particular time. Like conceptual versus expressed models, we suggest the distinction is useful because typical classroom practice does not include both of these aspects. The distinction between sensemaking and communication refers to the primary audience for whom the learners are creating the model. When sensemaking, individuals or groups are making a model *for themselves*, to try to understand a phenomenon, articulating their understanding as an expressed model to help clarify their thinking and make sure they agree within a group. For communication, the learners are at the point where they are ready to share their ideas with others, articulating their model to see if other agree, try to persuade others or help them understand the phenomena.

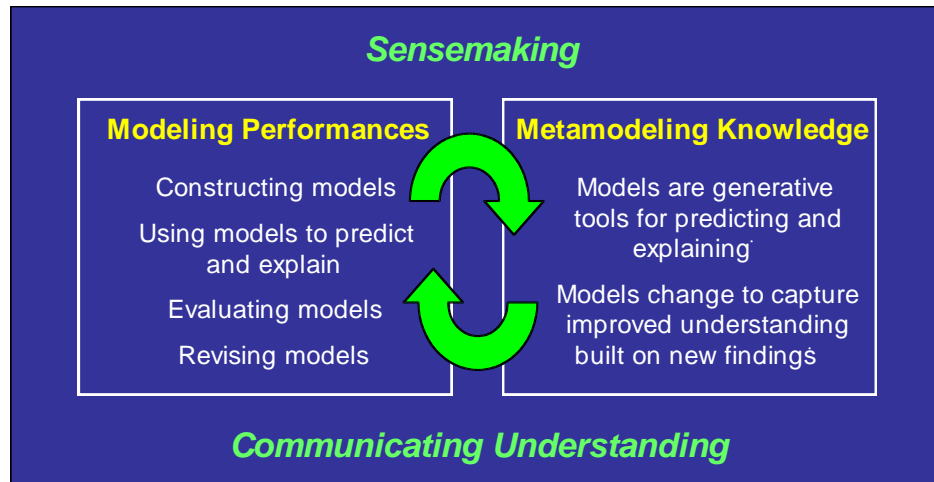


Figure 2. Modeling practice as the interaction of the performance aspects of the practices and metamodeling knowledge. The two types of goals, sensemaking and communicating understanding, each emerge from the use of performance and metamodeling knowledge.

We tease these dimensions apart because the idea of constructing models as supporting sensemaking (helping the modelers figure out a phenomenon) is new to most teachers, who think more of models created by students as ways to demonstrate understanding they have acquired in another context (Schwarz & Gwekwerere, 2007). Typically, if students need to learn about phenomena, teachers assume that models should be provided to them to manipulate (such as stream tables or computer models) where the accuracy of the model isn't questioned nor do students attempt to improve the model.

Generalizing Modeling Practice Beyond Specific Scientific Contexts

The third commitment in our learning progression design concerns the relationship between domains of scientific ideas and the learning of the practice. The influence that specific contexts have in learning scientific ideas is of course critical. Generalizing from specific problem contexts to form more general scientific and mathematical principles is a challenge in approaches that attempt to contextualize learning in meaningful problems (Barron et al., 1998; Kolodner et al., 2003; Lehrer & Schauble, 2006; Reiser et al., 2001).

However, with the focus of the learning progression on the practice of scientific modeling itself, rather than on learning specific scientific models, such as the particle model of matter or a systems model of interactions in ecosystems, we are focusing on how the practice of modeling itself improves. Thus, we look not only for improved

content in particular models, but for changes in how the modeling itself is being done, including the use or application of particular models in other systems and contexts. Our intent is not to minimize the importance of learning specific scientific models. Nor do we intend to minimize the challenges of generalizing understandings about what it means to build a successful model developed in one scientific context, such as modeling the interactions of light and material objects, to apply to another situation, such as modeling how particles travel through air. Our goal is to attempt to explore to what extent knowledge about modeling can be abstracted from the specific modeling contexts in which it is developed. We are open to uncovering ways that specific contexts need to be treated independently, as separate aspects of modeling knowledge. Perhaps understandings about modeling of physical phenomena are difficult to translate into understanding model practice to explain how living things behave. Furthermore, the nature of the model itself may pose different enough contexts that these need to be treated separately. Understanding static models that represent understanding, such as physical models or diagrams, may pose different challenges than dynamic models such as computer simulations, that can be caused to behave and can produce unexpected results. We hope to examine the ways in which understandings of core ideas such as fitting models to evidence, using models to generate new predictions, representing only central and relevant aspects of phenomena, and so on, are constrained by aspects of the context. However, a commitment to examine ways knowledge may carry from one setting to another is key if we are going to look for learning about this practice, which can be applied across a wide range of kinds of models and scientific phenomena.

Examples of Modeling Practice and Modeling Knowledge

What might such modeling practice look like implemented in elementary or middle grades classrooms? In the fifth grade classrooms, for example, students construct initial models for evaporation and later condensation, while at the same time discussing the nature and purpose of models; they gather data from experiments to test those models (such as evidence of water vapor increasing or decreasing in the air); they gather theoretical notions from the scientific community (such as observing simulations such as of water particles of water at the surface of a liquid evaporating in the air) and revise their models, while discussing and applying criteria for evaluating and revising models; they

construct a class consensus model, and apply it to other contexts that involve condensation and evaporation (such as paint or hair drying, condensation on a Coke can or on the bathroom mirror, etc.)

In 6th grade classrooms, students construct and revise three-dimensional and two-dimensional drawn models for how humans see an object, incorporating a light source, an object, an eye as the detector, and light rays. As the unit progresses, students revise the model to account for other light phenomena involving scattering, reflection, transmission, absorption, and color, enhancing the model's explanatory and predictive power. A second 6th grade unit on the particle model of matter includes constructing and revising models that indicate how someone might smell a scent from across the room based on molecules dispersing through air. The four aspects of constructing, using, evaluating, and revising, models are illustrated for these examples are described in Appendix A.

The metaknowledge interspersed in this work is critical in helping learners engage in these practices more reflectively. There are several aspects of metaknowledge that are incorporated or being incorporated in these approaches. First, students need to understand the purpose of models as explanatory tools in order to understand what they are trying to do in developing a model. They need to understand how to evaluate models in terms of their fit with evidence in order to figure out where the strengths and weaknesses of their models are, and how to improve them. Therefore they need to understand the criteria we apply to determine whether one model is more effective than another. Finally, they need to understand that models can be improved to reflect new understandings.

Putting the Pieces Together — Constructing the Learning Progression for Modeling

Our work in constructing a learning progression around modeling practice and metamodeling knowledge has leveraged our prior work (Schwarz & White, 2005; Zhang, Liu, & Krajcik, 2006), theoretical analysis with existing benchmarks and maps (AAAS, 1993, 2001, 2007), and empirical work on modeling and models (Carey & Smith, 1993; Grosslight et al., 1991; Smith, Maclin, Houghton, & Hennessey, 2000).

We represent the learning progression as a construct map of multiple progress variables, each of which shows levels of performance and understanding (Wilson, 2005). Our original attempt to articulate metamodeling knowledge identified three major

dimensions of understanding: nature of models, purpose of models, and criteria for evaluating and revising models. Some of the important aspects of understanding we identified as part of these ideas are show in Table 1. These individual assertions provide a sense of the various aspects of understanding we are trying to capture in the progression.

Table 1: Individual Understandings that Could be Included
in a Learning Progression for Modeling

<p><i>Nature of Models</i></p> <p>Models can represent non-visible and non-accessible processes and features</p> <p>Different models can have different advantages</p> <p>Models are representations that have limitations in what they represent about phenomena</p> <p>Models can be changed to reflect growing understanding of the phenomena</p> <p>There are multiple types of models: diagrams, material models, simulations, ...</p>
<p><i>Purpose of models</i></p> <p>Models are sense-making tools for constructing knowledge</p> <p>Models are communication tools for conveying understanding or knowledge</p> <p>Models can be used to develop new understandings, by predicting new aspects of phenomena</p> <p>Models are used to illustrate, explain, and predict phenomena</p>
<p><i>Criteria for Evaluating and Revising models</i></p> <p>Models need to be based on all the evidence about the phenomena</p> <p>Models need to include only what is relevant to their purpose</p>

As examination of the elements in Table 1 makes clear, there is much overlap between these potential dimensions, particularly between understandings about nature of models and purpose of models. As we developed candidate construct maps, interview protocols, and attempted to apply these construct maps to our pilot interview data, we attempted to consolidate these dimensions into two main themes mentioned earlier.

- *Models are generative tools for prediction and explanation*
- *Models are dynamic and subject to change as our understanding improves.*

The generative tools dimension is intended to capture several related aspects of growth. The central idea in this dimension is a transition from viewing models as representing static correct answers to seeing them as generative tools for thinking. Students can move from seeing models as capturing right answers to seeing them as useful tools for learning that illustrate or explain hidden aspects of phenomena, and then finally see models as helping those that have constructed the model to think through and explore different explanations about the phenomenon. Related to these changes are moving from seeing models as literally similar replicas of phenomena to being selective representations, with limitations, that represent features useful for prediction and explanation. This dimension also captures the sense idea that students at a more advanced level see models as representing useful explanations about phenomena, developed to be consistent with evidence. They use models to generate new predictions that can be tested against the phenomenon.

An example of lower level performance on the generativity dimension was observed in early pilots with 4th grade students. Students were asked to draw their model to show how they thought water traveled through plants. They drew their diagrams and discussed them, and then revised them after some conversations. Their revisions often added more detail, but the detail was not always relevant to the question they were attempting to explain, instead reflecting a more general school notion of “more detail is better.” Another lower level aspect of their performance was in being asked to make predictions from their model about an experiment in which celery was put into colored water. Most students essentially treated this as a new question, and generating predictions without necessarily drawing on their model for support, and in some cases generated predictions that were inconsistent with what they had said earlier in their expressed model.

We have been finding some evidence that the communicative aspects of generativity more accessible than the sensemaking aspects. The idea that models can help somebody learning about a phenomenon learn from someone else that knows more may be more intuitive than that something we ourselves build can help us learn more. Middle school students early in their modeling experience are able to comment on how working with the model presented by a peer helped them understand their peer’s ideas. For

example, one stated, “Well, it kind of explains and shows you what is actually in the air. Instead of just saying, ‘Oh, there’s empty space there,’ they’ll be like, ‘What do you mean?’ So if you have a model, you can actually show them, and it might explain it better.” Another student stated, “The purpose of modeling is to be able to explain what you’ve learned so far, and pretty much ... what you think.”

In a construct map designed around the second dimension of *models as a dynamic tool for sensemaking*, a student with very beginning notions of modeling (level 1) might think about models as fixed entities, either right or wrong, and serving only to show that you know something. At the next level (2) a student might see that models can be improved, but does not understand these changes as an outcome of growing understanding. At this level, we might observe students revising their models to account for information from an authority (teacher, textbook) without connecting this model change to the range or accuracy of phenomena that can be captured. In addition, they might revise models to make them nicer and to improve their details in literal similarity, but not improve the explanatory power of the models by clarifying the entities and relationships in the model.

At a more experienced level, (level 3), a student might begin to understand that their models need to be revised to account for new evidence and to represent their new understanding of the phenomena. They may understand that the model has explanatory power, but not predictive power. For example, a level 3 student would modify a model to account for evidence (authoritative information, empirical, etc.) as well as modifying the model entities and relationships to better fit with the phenomena (thus improving the explanatory power). A student at this level realizes that when encountering new evidence, the model may need to be revised in order to fit with what is now known about the phenomenon.

Students in middle school units focusing on modeling began to realize that new findings might require changes in their models to improve their fit with the cumulative set of data. For example, one student said in an interview, “I think there can be a right model, but in our class, I don’t think anybody’s had the perfect model yet because some people came really close to having a good model, but there was always something that

was missing in it. So we would always do more experiments and stuff to help us add or learn new things to a model.”

Students in the middle school classrooms were also aware that their models had limitations and made statements such as, “if you want to see how it moves, and you just draw arrows, you can’t really see it actually moving and bumping into each other and bouncing on the walls and stuff. . . .because it doesn’t really show that it can bounce on the walls and bounce into each other; it just shows that it’s moving.” Another stated, “Like what Jo said, but you can’t--some models can’t show how fast the particles or molecules are moving.”

Level 4 modelers understand that models can be truly generative, and are useful because they can draw out new explanations and predictions. While previous levels worked primarily from phenomena to models (see Figure 1), this level of understanding works back and forth between models and phenomena. These modelers understand that in evaluating a model, one draws out the implications and tests them against the phenomenon, and that doing so might yield new kinds of observations that need to be collected. If the model turns out to be correct in its predictions, the model has led to an increased understanding about the phenomenon. Learners at this level might discuss possible changes to their models depending on the evidence to be collected, before the models are tested. Students at this level might also compare alternative components or relationships in the models with competing models to consider how to enhance the explanatory power of the model or to decide which model is most useful in different situations. They realize that there may not be one right model, and that it may not be possible to determine whether one model is superior to another in absolute terms, instead it depends on questions one is trying to address with the model.

Studies of Student & Teacher Learning

Our learning progression is being implemented and tested in multiple grades – those at the elementary (4th/5th) grade levels, and those at the middle school levels (6th and 7th grades). Our goal is to conduct a grade band comparison of late elementary with middle school students in the same science domains. A longitudinal study is also being conducted within the middle school (6th through 7th grades) as students progress through multiple science content topics.

Our studies are also focused on teachers as they learn to support their students in modeling practice. We are working with pre-service teachers and in-service teachers to determine the kinds of learning and support they need to understand and carry out these practices in the classroom. We are not developing a complete learning progression articulating the trajectory to characterize the evolution of teachers' understanding, although that would be an interesting and useful goal. Rather, we are investigating the supports necessary for teachers to be successful in effectively engaging their students with modeling.

Our research is designed to investigate several questions. (1) Are students engaging in modeling practices? What is the nature of that engagement? (2) Are they developing modeling practices and metamodeling knowledge over time (across the grade)? (3) How different do the practices and the knowledge look across grade bands? We have also focused on additional research questions such as: what challenges do students and teachers face while engaged in modeling? What instructional supports promote student and teacher learning of the practice and knowledge? What relationship is there between the disciplinary knowledge, the practice, and the metamodeling knowledge? Is the practice appropriated by students and teachers and transferred to new contexts?

The other papers in this paper set describe our elementary, middle school, and teacher education studies. All of these studies have designed curriculum materials foregrounding modeling and implemented those materials in classroom to determine the outcomes. Data collected include: pre-post written assessments, classroom artifacts, classroom discourse, and interviews. Each paper will describe the design of the interventions, that analysis of their data, outcomes from that work, and challenges and opportunities of that work. The final paper in this paper set will synthesize outcomes and implications for future directions.

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Appendix A: Four aspects of modeling practice in different curricular contexts

Modeling Practices	Construct	Use	Evaluate	Revise
<p>5th Grade Evaporation & Condensation Unit.</p> <p>Driving question: <i>“Would you drink the liquid that came from this dirty water?”</i></p>	<p>Students construct initial models to describe, explain and predict evaporation and later condensation.</p>	<p>Students apply their consensus models to contexts that involve condensation and evaporation such as paint or hair drying, condensation on a Coke can or on the bathroom mirror, and the solar still.</p>	<p>Students evaluate their models with respect to the evidence they gathered from experiments to test those models (such as evidence of water vapor increasing or decreasing in the air), as well as with respect to theoretical notions introduced from scientific simulations (such as particles of water at the surface of a liquid evaporating in the air).</p>	<p>Students revise their models after analyzing the empirical and theoretical evidence, and they construct a class consensus model from these revisions.</p>
<p>6th grade IQWST Light Unit</p> <p>Driving question: <i>“Can I believe my eyes?”</i></p>	<p>Construct an initial three dimensional model for how humans see objects with light</p>	<p>Application of the light model to familiar phenomena (shadows) as well as to phenomena that the model cannot explain.</p>	<p>Evaluate the model with respect to the empirical evidence.</p>	<p>Students revise their initial light model to make it easier to use (2 dimensional), to account for additional light phenomena including scattering, reflection, transmission, absorption, and color, and to create a consensus models.</p>
<p>6th grade IQWST</p>	<p>Students construct initial models</p>	<p>Students use their initial models</p>	<p>Students evaluate their models</p>	<p>Students constantly discuss</p>

<p>Smell unit Driving Question: <i>How can we smell an odor from a distance?</i></p>	<p>to explain how an odor can get their noses.</p>	<p>to explain the behavior of different gases (such as air compression and expansion, of ammonium vapor).</p>	<p>by comparing with peers and assessing evidence from readings and experiments (such as different liquids changing to gases)</p>	<p>different ways of changing their models to enhance the explanatory power (including different aspects of the phenomenon in their models, assessing new data, or addressing a wider range of phenomena such as different molecular behaviors or different room temperatures).</p>
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