MODELS: DEFINING A LEARNING PROGRESSION FOR SCIENTIFIC MODELING

The MoDeLS project, *Modeling Designs for Learning Science,* is developing a learning progression to represent successively more sophisticated levels of engagement in and knowledge of scientific modeling. Our goal is to make this core scientific practice accessible and meaningful for learners in the upper elementary and middle grades. We define scientific modeling as including the elements of the practice (constructing, using, evaluating and revising scientific models) and the metaknowledge that guides and motivates the practice (e.g., understanding the nature and purpose of models). Our learning progression for scientific modeling includes two dimensions that combine metaknowledge and elements of practice — *scientific models as tools for predicting and explaining*, and *models change as understanding improves*. In this paper, we focus on defining our learning progression by outlining our levels of progress within the *models as tools* dimensions of our progression, defining what progresses between these levels, and describing the evidence we are using to evaluate and refine our progression. We conclude by discussing several challenges of designing a progression for a scientific practice and implications for future work.

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Introduction

The MoDeLS project, *Modeling Designs for Learning Science,* is developing a learning progression to represent successively more sophisticated levels of engagement in and knowledge of scientific modeling (Schwarz, Reiser, Davis, Kenyon, Acher, Fortus, Swartz, Hug & Krajcik, in press). Our goal is to make this core scientific practice accessible and meaningful for learners in the upper elementary and middle grades. A scientific model is an abstract, simplified, representation of a system of phenomena that makes its central features explicit and visible, and can be used to generate explanations and predictions (Harrison & Treagust, 2000). The practices involved in developing and using models are central in authentic scientific practice. Involving learners in model-based practices can help them build subject matter expertise, epistemological understanding, and expertise in the practices of building and evaluating scientific knowledge (Lehrer & Schauble, 2006; Lesh & Doerr, 2000; Schwarz & White, 2005; Stewart, Cartier, &

Passmore, 2005; White & Frederiksen, 1998). The opportunity to engage in scientific modeling is critical for developing and evaluating explanations of the natural world.

Scientific modeling, however, is rarely incorporated into educational experiences of elementary or middle school students. When modeling is incorporated into school experiences, it is often reserved for older learners and primarily used for illustrative or communicative purposes, thus limiting the epistemic richness of the scientific practice (Windschitl, Thompson, & Braaten, 2008).

Effective designs for science learning require considering which aspect of expert practice are productive for learners. The goal of our work is to develop a learning progression that characterizes the aspects of modeling that can be made accessible and meaningful for students and teachers. A learning progression articulates successively more sophisticated versions of the knowledge that is built on the understandings learners bring to the classroom (Duschl et al., 2007; Smith, Wiser, Anderson, & Krajcik, 2006). It is distinctive from other developmental approaches in that it is often content or practice-specific, not-necessarily linear, and can be used to characterize learners' progress with or without the support of instruction. Learning progressions offer the opportunity to explore how students build their knowledge and practices over time across a variety of important contexts such as curriculum materials and classroom environment. As such, learning progressions may be particularly useful for designing effective instructional materials, designing formative & summative assessments, and supporting effective instruction that can help learners meaningfully engage in the content and practices over time.

In this proposal, we outline some of the arguments for our learning progression for scientific modeling. In doing so, we address what is progressing in our learning progression, we describe the levels of that progression, and what evidence we use for evaluating and refining the progression.

Defining the practice of scientific modeling

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; Treagust, Chittleborough, & Mamiala, 2002; White & Frederksen, 1998). We define a scientific model as a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena. Examples 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.

Scientific modeling is a rich practice, and contains many candidate aspects in which designers might choose to involve learners. The goal of developing a learning progression for school science learners is to identify what forms of modeling and its underlying knowledge are tractable and productive for learners.

One important commitment in our learning progression design is the integration of the metaknowledge and elements of the practice. It is important that learners acquire an understanding of the roles of models and modeling in science. This knowledge about modeling is a type of nature of science understanding (Lederman, 2007) that we refer to as *metamodeling knowledge* (Schwarz & White, 2005). Learners need to understand how models are used, 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 (Abd-El-Khalick et al., 2004).

It is also important that students learn to engage in the modeling practice itself – that is embodying key aspects of a theory and evidence into an expressed representation; using the representation to illustrate, predict and explain a system or phenomenon; and evaluating and revising the representation as it is used. Based 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; Schwarz & White, 2005; Snir, Smith, & Raz, 2003; Spitulnik, Krajcik, & Soloway, 1999; Stewart, Cartier, & Passmore, 2005), we have operationalized the practice of modeling to include four elements that we target:

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

We argue that elements of the practice and the metaknowledge should not be viewed as separate learning goals. The practice and underlying knowledge are significantly more powerful and meaningful when addressed with one another rather than as separate components. Therefore, our learning progression specifies the aspects of metaknowledge that influence the elements of the practice, and we attempt to support and look for growth in the interaction of metaknowledge and these elements of practice.

A related issue in the connection between metaknowledge and practice is the role of specific domains of scientific phenomena (such as heredity, nature of matter, ecosystem dynamics) in the progression. The influence that specific contexts have on learning scientific practices is critical (Lehrer & Schauble, 2006; Tabak & Reiser, 2008). However, our learning progression focuses on the practice of scientific modeling itself and how it can become more sophisticated with appropriate learning experiences, rather than on how particular ideas are developed (such as the particle nature of matter or a systems model of interactions in ecosystems). Thus, we look not only for improved content in particular models, but for changes in how the modeling itself is being done. Our intent is not to minimize the importance of learning specific scientific models. Our goal is to explore to what extent knowledge about modeling can be abstracted from the specific modeling contexts in which it is developed. A commitment to examine ways knowledge may carry from one setting to another is important if we are going to look for learning about this practice, which can be applied across a wide range of models and scientific phenomena.

Our learning progression for scientific modeling

We represent our learning progression for scientific modeling as a set of related construct maps of progress variables, each of which shows levels of performance and understanding (Wilson, 2005). Each progress variable for modeling represents a trajectory of more complex aspects of this practice and its associated understandings that we expect students to exhibit in classroom modeling activities. Each level of performance within a variable represents a more sophisticated version of the previous level of performance.

We organize these performances and understandings in two dimensions, each of which incorporates the four elements of practice and the metamodeling knowledge that guides the practice. The two dimensions concern the generative nature of models as tools for explaining and predicting, and the dynamic nature of models as improving with new understanding. These dimensions have emerged as more useful than organizing the analyses of the level of students' performance according to the four elements of practice (i.e., construct, use, evaluate, and revise) because of overlapping elements of practice and similar metamodeling knowledge. Instead, we identified two clusters of issues in understanding models that influence all four elements of practice. The generativity of models dimension organizes understandings about how models explain new aspects of phenomena, and is useful in guiding what kinds of models to create and ways to evaluate and then revise them. The dynamic nature of models dimension organizes understandings about when models need to change, and thus guides model construction, evaluation and revision.

Each dimension attempts to characterize reflective practice — the combination of students' performance of the task (both process and product), accompanied by the underlying metaknowledge that makes the activity meaningful. Thus the construct map analyzes the modeling process students exhibit (such as the decisions they make about revising models), their reasoning products (such as properties of their constructed models or types of changes in a revised model), and their understanding of these performances (as reflected in their discourse or written explanations). Furthermore, each level is associated with significant rather than incremental differences in reflective practice and broadly describes the reflective practice. In other words, the level changes incorporate fundamental shifts in reflective practice. Describing fundamental shifts is useful for broadly characterizing and testing the core variables and enables subsequent elaboration of finer-grained sub-levels found in the data.

To illustrate our work, we present one of the two dimensions of our learning progression in Table 1 – *models as generative tools for predicting and explaining*. (The other dimension is included in Appendix A.) This *models as generative tools* dimension focuses on how students construct and use models, whether the models embody explanatory aspects of phenomena (e.g., mechanisms, processes), and whether students view models as useful for advancing their own knowledge as well as helping communicate what has been learned to others. Each of the four levels is shown with two related performances that exemplify the level. Those performances are meant to encompass students' decisions about the components and relationships to include when constructing and using a model. The later includes what purposes students have when constructing and using models.

Level	Performances
4	Students *construct and use models spontaneously* in 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 more 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 posses.
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 *means of communicating their understanding of a phenomenon* rather than a tool to support their own thinking.
1	*Students construct and use models that show literal illustrations of a single phenomenon*. Students do not view a model as tool to generate new knowledge, but do see models as *a means of showing others what the phenomenon looks like*.

Table 1. A Learning Progression for Understanding Models as Generative Tools for Predicting and Explaining

At Level 1, students construct and use models that show literal illustrations of a single phenomenon. Students at this level view models as a means of describing the phenomenon to others, rather than explaining why it occurs. This initial level can be seen in many of the elementary students' initial modeling work, and in some aspects of middle school students' work. These initial models are veridical illustration of the phenomenon under study, depicting only observable features, rather than attempting to explain the phenomenon. For example Figure 1 illustrates a 5th grade students' initial model of water in a covered and uncovered cup. The student has drawn the cup and lines indicating the water level before and after a period of time, but there are no explanatory constructs in the diagrams. Additionally, some students talk about models in ways that are consistent with this level. For example, one student studying condensation stated, "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 …" Students view the purpose of constructing and using models at this level as duplicating reality and illustrating one correct idea. For example, one student stated, "One of those models are the right prediction, and it really could happen in the real world."

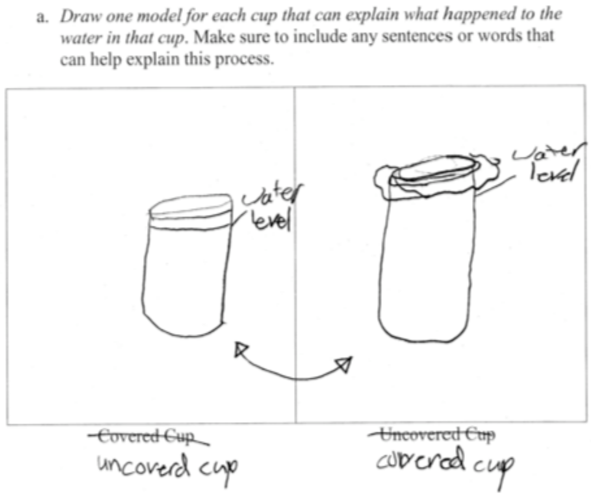

Figure 1. A 5th grade students' pre-test model of water in a cup illustrating a Level 1 on the *Models as Generative Tools* construct map

Level 2 embodies the fundamental shift that students construct and use a model to explain *how* a phenomenon occurs and this model is consistent with evidence about the phenomenon. These explanations might include non-observable processes, mechanisms, or structural components that help to explain the phenomenon. Students also consider observational or experimental evidence as well as authoritative evidence from the teacher, textbook, or other sources. Furthermore, students at this level view models as a means for communicating their understanding of a phenomenon. However, they do not yet view models as tools to support their own thinking. Figure 2 illustrates the 5th grade students' post-test model of a covered and uncovered cup. In the diagram, the student has included microscopic particles in a 'zoomed – in' fashion to illustrate how the water is condensing as well as escaping. The student has also included arrows indicating a process and direction for the evaporation as well as labels to show that the water level has changed in the open cup - illustrating a change over time. The inclusion of non-visible processes, mechanisms and components help to explain the phenomenon. This item by itself does not enable us to determine whether this student is above a level 2 in reflective practice – as we would need to know how the student was using the model and whether or not the student considered alternative components.

In addition to the diagrammatic models, students illustrating aspect of a Level 2 reflective practice refer to the explanatory nature of the model their assessments and interviews. For example, "The models are helpful because they explain how evaporation and condensation works. ..." One 5th grade student wrote that something is a model "because it just doesn't show a picture or a diagram. …It explains the kinetic energy. It explains the molecules in the air, and the particles vibrating. It doesn't just show it, it explains." This student explicitly rejects the Level 1 notion of veridical illustration of the phenomenon that was more common in these students' initial models. Some students illustrating aspects of Level 2 also mention that models serve to communicate explanations and one's thinking to others — for example, to "show what you're talking about" and help "explain to the others."

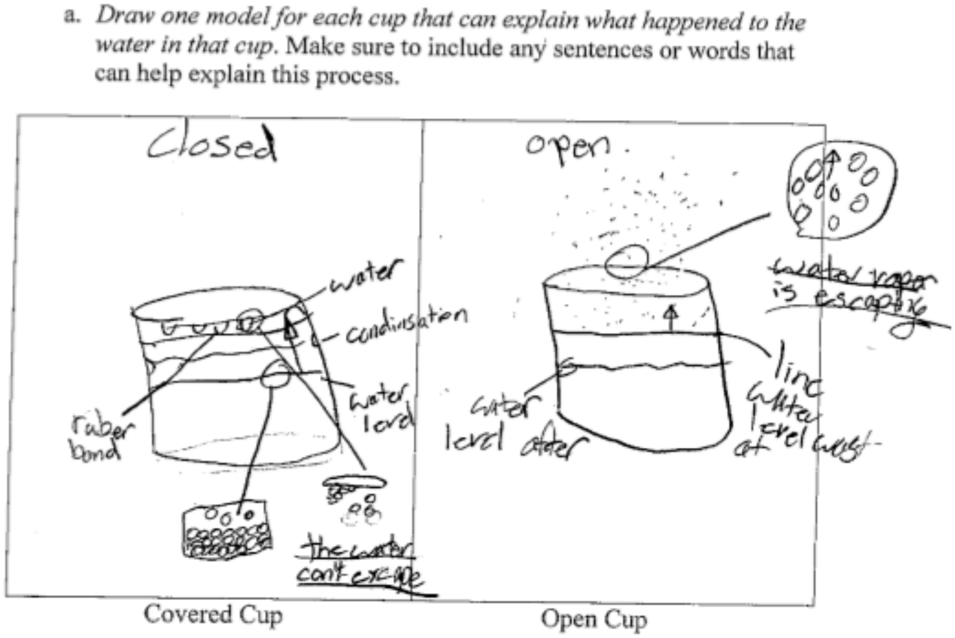

Figure 2. The 5th grade students' post-test model of water in a covered and uncovered cup illustrating Level 2 on the *Models as Generative Tools* construct map

Level 3 adds complexity in several aspects of modeling. The level brings a focus not only on explaining observed phenomena but also on generating predictions about new phenomena related to what they have studied. In addition, at this level students' models explain a cluster of related phenomena, and this may require constructing multiple models. Students may consider alternatives in constructing models, evaluating the advantages and weaknesses of the models for explaining and predicting phenomena.

Evidence indicating a level 3 reflective practice might show students drawing explicitly on prior models to extrapolate to new phenomena, suggesting that the student sees the model as useful for explaining new phenomena. We see some aspects of Level 3 in elementary students' written post-tests, as students apply explanatory models learned in one context to explain new (but related) phenomena. For example, students were asked to "use one of the models you drew [in the first part of the question] to explain what happens to your color marker when you leave the top off of it for a week." One student wrote, "In the model of the cup with no lid, the water is evaporating into water vapor or gas, and that's what happens with the marker because it's a liquid and all liquids evaporate into a gas or water vapor." This student is explicitly drawing on a prior model and using it to predict the behavior of a different but related phenomenon.

We see other evidence of a Level 3 reflective practice when students apply or indicate they can apply their model to predict the behavior of other phenomena beyond the examples they used to construct it. The following interview excerpt serves as an example:

Researcher: Could a model like the models you have done help you to understand something that you don't know yet? Just to predict?

Sean: Yes 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.

Finally, the Level 3 consideration that models need to explain multiple related aspects of a phenomenon can be seen in some 6th grade students' discussions of how their models connect to their investigations. For example, one student has drawn two related models, one to explain how air can be compressed into a smaller space, and one to explain how it can expand to fill more space, but draws on the same underlying explanatory model, namely the existence of empty space between moving air particles. In discussing the models, she states:

Well, we're probably drawing different models because, when the plunger part of the syringe is out, there's going to be a different activity with the air going on than when the air's compressed and when the plunger is farther down towards the tip.

Level 4 reflects the goal that students construct and use models spontaneously in a range of domains to help their own thinking. Students consider how the world could behave according to various models, and they construct and use models to generate new questions about the behavior of phenomena. This focus on developing questions has not emerged in our own elementary and middle school classroom trials, perhaps due to the constraints of school science in which the curriculum and teacher have a strong hand in guiding students into particular questions. However using models to advance scientific knowledge by generating questions to guide research is fundamental to understanding knowledge building in science (Carey & Smith, 1993; Lederman, 2007; Lehrer & Schauble, 2006).

Testing our learning progression

We are currently engaged in an iterative process of refining the two dimensions of the learning progression against empirical work within multiple classroom trials as part of an empirical validation process (Anderson, 2009). Those classroom trials are taking place in 4th , 5th, and 6th grades throughout the Midwest, using scientific modelling curricula we have developed to support teachers and students at engaging in the practice. From these classroom trials, we are collecting evidence of students' reflective practices from written pre-post assessments, student artifacts in the classroom, classroom talk, and interviews. Capturing students' engagement in the practice as well as their conversations and discussions about decisions related to the practice is critical for determining students' progress in the practice because much of the reflection and decision-making is tacit. Analyses of students' understandings about their modeling practices helps uncover important aspects that may need to be captured in the construct maps. For example, we are currently exploring the multiple different aspects of practice that might emerge in a level 2 understanding, determining what kind of evidence is needed to exhibit this understanding and what are the important elements that distinguish this level from the others.

We illustrate how we have begun to further unpack Level 2 in our "*Models as generative tools*" construct map. To reiterate, Level 2 describes two important aspects: (a) students construct and use a model to illustrate and explain how a phenomenon occurs, consistent with the evidence about the phenomenon and (b) students view models as means of communicating their understanding of a phenomenon rather than a tool to support their own thinking. In Table 3, we describe sub-levels and components of Level 2 that match emerging patterns from analysis of students' interviews and written assessments. For example, a strong indication of a Level 2 reflective practice might entail a student considering empirical evidence or mechanism while constructing their model and discussing how the model is important to explain how the phenomena occurs. A weaker instance of a Level 2 reflective practice might entail a student constructing a model with invisible components and stating that the model is useful for helping others to understand. The former is closer to an understanding and use of models as generative tools for predicting and explaining; the latter is closer to an understanding and use of models as illustrations of the word for communication. Both entail constructing or using models to describe or explain how a phenomena occurs for the purposes of communication with others.

	How do Ss select and make decisions about including components and relationships when they construct and use models?	What purpose Ss have when constructing and using models?
Level 2	a) Ss consider observational or experimental evidence b) Ss consider authoritative evidence (from teacher, textbook, respectable source) c) Ss consider evidence of personal opinions (from peers, own knowledge, family, etc.) d) Ss construct/use model to explain phenomenon with mechanism e) Ss construct/use model to explain phenomenon with process f) Ss construct/use model to explain phenomenon g) Ss consider non-visible processes or mechanisms h) Ss consider non-visible structural components	a) Purpose is to explain the mechanism of a phenomenon b) Purpose is to explain the process of a phenomenon c) Purpose is to show change over time d) Purpose is to explain a phenomenon f) Purpose is for others to understand

Table 3 Sub-levels and components of Level 2 reflective practice in the "Models as Generative Tools" construct map

While these sub-levels and components are still being revised to account for data from multiple sites, they provide some ideas about the natural variation of students' reflective practice and how that might be assessed in Level 2. Furthermore, they illustrate a finer-grained level of the reflective practice than those in our construct maps. We are finding that these finer-grained descriptions may be particularly important to capture changes in students' reflective practice as the curriculum, enactment, and assessments enable students to shift within level 2, but make it challenging to move beyond it. A more detailed description of the levels will enable us to determine how to better support learners, design more effective curriculum materials and provide more effective instruction.

Results from these revised construct maps are now being tested against data from additional classroom-trials that will then enable further revision of the construct maps. We may also conduct additional cluster analysis of our written assessment items and discourse analysis of classroom enactments to determine important factors that we can compare to the construct maps and to obtain riches cases of practice that can be compared with the paths and elements in our construct maps.

Challenges in constructing a learning progression for a scientific practice and implications for future work

Some theoretical and methodological challenges arise when developing a learning progression for a practice rather than an aspect of scientific understanding, such as the nature of matter (Smith et al., 2006). One particular challenge is the integration of the performance of the practice with underlying metaknowledge. We have chosen to assess the combination of practice and knowledge, so as to avoid teaching and assessing routine procedures on the one hand, or decontextualized understandings about science on the other hand. However, doing so makes more complex the grain size of elements in a construct map, and the associated analytical tools for analyzing student work and discourse. This issue is made even more complex when layering the science content area along with the reflective practice. Assessing reflective practice within and across science content areas has proven to be challenging. We are currently analyzing written assessment data and classroom discourse across multiple classroom contexts to address some of these issues.

A second and related issue is that metaknowledge does not consist of isolated disconnected fragments. The various aspects of what we understand about a practice interact. For example, understanding how to evaluate a model is clearly influenced by understanding why models are initially created and how they are used to develop knowledge. We have attempted to balance these challenges against the benefit of being able to track and assess reflective practice. We suggest these dimensions are relatively discernable in students' reflections and in their performances, despite their clear influence on one another. In future work, we will continue to explore both more fine-grained descriptions of students' reflective practices, as well as longer term longitudinal changes, in order to further evaluate these theoretical constructs in characterizing this scientific practice.

These challenges of designing a learning progression for a scientific practice point to additional future work. Because of the complex nature of scientific practice, the construct maps themselves provide a framework for capturing students' progressions, but may not provide adequate information about what meaningful and productive practice looks like in the classroom or how to generate effective curriculum material design, instruction or assessments for such a practice. As a result, rich descriptions are needed of the nature, successes and challenges of the various levels of practice and their contexts along with the learning progression framework. Such work is necessary to enable learners to appropriate scientific practices as part of their scientific literacy (Duschl et al., 2007).

In addition, we need to continue developing our underlying theories for how learning to engage in reflective practice occurs and how this can be represented in our learning progression. While we understand that appropriating new scientific practices involves acquiring underlying knowledge (about the subject matter, about the nature of the practice) as well as participating in new practices in particular communities for certain purposes, we are still conceiving how the elements and combination of these and other aspects enable learners to move among levels of reflective practice in our learning progression. When does a learner or a community of learners need particular scientific evidence or content information along with scaffolds for engaging in practices of data collection, analysis, model construction, evaluation, revision, and argumentation that poses explanations and predictions? How do they need to participate in those practices and when? When might such learners need just-in-time reflective dialog about the purposes and meanings of the practices related to science ideas? Our data analysis is providing promising patterns that we need to further analyze.

Finally, the complex nature of the practice as one important element of science learning may indicate that future learning progressions may take a different form such as descriptions of ecological-like systems of knowledge, practice, and identity along with their contexts to describe how these components evolve over time. For now, we continue to work on refining our construct maps, validating them, and developing rich descriptions to enable a better understanding of how such learning progressions can enable us to make scientific practices accessible and meaningful for learners.

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Appendix A

Our Second Construct Map: Understanding Models as Changeable Entities

Level	Performances
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 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 how 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, clarity or 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 assessing if they are *good or bad replicas of the phenomenon*.