Supporting Sophisticated Modeling Practices in Secondary Science

Ashlyn Pierson, Vanderbilt University, ashlyn.pierson@vanderbilt.edu
Doug Clark, University of Calgary, douglas.clark@ucalgary.ca
Max Sherard, University of Texas-Austin, mksherard@utexas.edu

Abstract: Schwarz and colleagues proposed a learning progression for modeling that provides a valuable template for envisioning increasingly sophisticated levels of modeling practice (Fortus, Shwartz, & Rosenfeld, 2016; Schwarz et al., 2009; Schwarz, Reiser, Archer, Kenyon, & Fortus, 2012). Thinking about learning progressions for modeling, however, involves challenges in coordinating between aggregate curricular arcs and supporting individuals' learning. First, students' purposes for modeling and the nature of the context shape individual student performances. Second, approaches for longitudinally supporting students in modeling is a relatively nascent endeavor. Third, research on the highest levels of the progression is often hypothetical, because few students demonstrate high-level practices in classrooms. In response to these challenges, we partnered with an eighth grade teacher in a semester-long design-based study. In this paper, we explore conceptual and representational contexts designed to support sophisticated modeling practices and beliefs and analyze the nature of high-level performances achieved through these contexts.

Introduction

Internationally, researchers and practitioners recommend increasing K–12 students' engagement in authentic scientific practices such as modeling (e.g. Louca & Zacharia, 2012; National Research Council [NRC], 2012; Östman & Wickman, 2014). In service of these goals, Schwarz and colleagues have proposed and refined a learning progression for modeling to support students in developing modeling epistemologies and practices (Fortus, Shwartz, & Rosenfeld, 2016; Schwarz et al., 2009; Schwarz, Reiser, Archer, Kenyon, & Fortus, 2012). Thinking about learning progressions for modeling, however, involves challenges in coordinating between over-arching aggregate arcs in the curriculum and individual student learning trajectories within the curriculum. In response to these challenges, we conducted a semester-long design-based study of eighth graders engaging in multi-modal modeling. In this paper, we explore contexts designed to support increasingly sophisticated modeling practices and beliefs. Specifically, we explore conceptual contexts (the phenomena students were studying) and representational contexts (the types of models students were encouraged to construct) that support increasingly sophisticated modeling practices and beliefs by typical students in a low-SES, high-diversity public charter school and analyze the nature of high levels of performance achieved through the designed curriculum.

Learning progression for modeling

For this paper, we focus our design and analyses around Schwarz and colleagues' (2012) articulation of a learning progression for modeling (see Table 1) (Fortus et al., 2016; Schwarz et al., 2009, 2012). During the development of the learning progression, however, Schwarz and colleagues found few students engaging in Level 3 practices and no empirical evidence of students performing Level 4 practices (Schwarz et al., 2009, 2012). It is therefore important to continue exploring conceptual and representational contexts that support middle school students in engaging with high-level modeling performances. Our research explores conceptual and representational contexts designed to support sophisticated modeling practices and beliefs.

Table 1: Schwarz and colleagues' progression (adapted from Schwarz et al. (2012) and Fortus et al. (2016))

Category	Levels
A. Salience-generality	1. Models are literal illustrations of a single phenomena 2. Models consider things that are inaccessible to the senses and can represent multiple similar phenomena 3. Multiple models can represent the same phenomena, and one model can represent multiple phenomena 4. Models can represent unknown phenomena or ideas
B. Audience/user	1. Models are made for the teacher □2. (A) Models are made to show what I think (B) Models are made to help others understand

	3. Models are made to communicate with others 4. Models are made to help me think
C. Evidence	1. No justification needed 2. (A) Content knowledge (B) Authority (C) Evidence in a specific case 3. Evidence in general with a justification for how evidence supports claims
D. Mechanistic-generative	1. Descriptive only 2. Illustrate with a vague sense of explaining and predicting 3. Represent a mechanism to explain a predicted phenomena 4. Predict and generate questions about possible new phenomena
E. Revision	1. Models are not revised; they are either right or wrong 2. Revised to better fit information from authorities 3. Revised to better fit evidence obtained 4. Revised to enhance explanatory and predictive power

Design conjectures

The high-level conjecture guiding our work was that Level 4 modeling practices could be supported by engaging students in several representational contexts by encouraging them to construct and coordinate across three types of models: diagrammatic models (drawings that communicate explanatory mechanisms), physical models (material objects created to test mechanisms), and computational models (runnable simulations created by programming explicit rules for groups of actors in a system). We conjectured that creating and interrelating multiple types of models would serve to support students in using models as tools because shifting between models would position the models as resources rather than as final products. We further conjectured that shifting among models would support students in revising their models to increase their explanatory power or empirical accuracy, because each model they constructed would provide a new perspective of the phenomenon that they were studying. We situated these models within a complex and tangible conceptual context, which we conjectured would provide opportunities for creating abstract, generative models by encouraging students to highlight aspects of phenomena and by enabling students to root their models in evidence they collected. We embodied this conjecture by grounding the students' work in the ecological relationships in the school's garden, which has proved a powerful context in prior research (e.g., Manz, 2012).

Participants and intervention design

This semester-long study was conducted in a public charter school located in a large metropolitan school district in the southeastern United States in partnership with Max, the third author, and his three eighth grade science classes (91 students). At this school, 85% of the students qualify for free and reduced lunch. The school is culturally and linguistically diverse; 53% of students identify as Black or African American, 31% as Hispanic or Latino, 15% as White, and 1% as Asian. Students with disabilities make up 11% of the school, and 8% of students are English Learners. Max and the first author, Ashlyn, codesigned and cotaught the lessons. Lessons took place twice a week during students' 55-minute science class periods over the course of 5 months (33 days total).

This project consisted of three cycles. During each cycle, students chose to focus on a new research question. Students developed their Cycle 1 research question as a class during their first encounters with the garden as they observed that some parts of the garden were more moist than others. Then, they worked in small groups of three to five students to construct models to investigate the relationship between soil moisture and a variable of the group's choice, such as depth of soil, roots, or shade. The students began by observing the garden and drawing diagrammatic models that highlighted patterns they noticed. Then, they tested the relationships within their models in their classroom with physical microcosms and computational models. Though most groups' findings were straightforward, groups that investigated roots presented inconclusive findings.

Therefore, in Cycle 2, Max and Ashlyn encouraged students to investigate roots. Each group constructed models to explore the relationship between roots and their surrounding environment in terms of a variable of their group's choice, such as symbiotic relationships with bacteria and fungi, transpiration, hydrogen pumps, and root growth through mitosis and elongation. In this cycle, students began by using online research to draw diagrammatic models of their predictions about these mechanisms. They tested these relationships with both physical and computational models and used data collected from the physical and computational models to revise their diagrammatic models to improve the models' accuracy and explanatory power.

This work increased students' awareness of ecosystem services provided by plants, and several students suggested researching phenomena in which plants performed services that could benefit their school community for Cycle 3, such as phytoremediation of heavy metals in soil, carbon sequestration, and the absorption of airborne toxic chemicals. During this cycle, students did not have time to engage with physical and computational models; however, they created diagrammatic models based on their predictions and online research, presented their models to younger students, and selected species to grow at the school.

Data collection and analysis

During each class period, we collected video recordings of the classroom, audio recordings of Ashlyn's conversations with students during group and individual work, student artifacts such as models and written reflections, and Ashlyn's field notes from each class period. In addition to this detailed longitudinal data collection, we also collected baseline and summative data at the beginning and end of the project to provide benchmarks for student progress over the course of the semester. Data analysis necessarily unfolded in relation to students' participation in our design. Our ongoing analysis was critical to informing the evolution of the curriculum and supports for students. We focused our analysis on evaluating and revising our conjectures about how to support students in engaging more frequently in Level 3 and 4 modeling conceptions and practices.

Challenges and opportunities

We present the challenges and opportunities identified in our work by category of the learning progression. For each category, we describe our initial conjectures about supporting students in higher levels of modeling. Then, we analyze of the nature of high-level performances to operationalize Level 4 modeling practices achieved in these conceptual and representational contexts.

A. Salience-generality

Initially, we conjectured that interaction with diagrammatic models would support high-level practices in the salience-generality category because students would be encouraged to consider the inclusion and exclusion of different aspects of phenomena in the representational context of static, two-dimensional representations. However, on Day 2 when students created their first diagrammatic models of the garden, 65% of students created literal representations (Level 1). We conjectured that most students created literal models because the students had not yet established criteria for determining what was relevant or irrelevant in their models. Therefore, on Day 4 of Cycle 1, we encouraged students to use their models to represent a pattern that they noticed in the garden and to propose an explanation for their pattern. About 50% of the students represented unseen phenomena in their models and about 75% of the students created abstract models. Our current conjecture about this activity is that the goal of representing a mechanism is one way to support students in representing abstract and unseen phenomena (Level 2) rather than creating literal models (Level 1) because focusing on a mechanism provided students with a lens for what was important to include in their models.

In terms of high-level practices, the Schwarz and colleagues' progression proposes that Level 4 performances in the salience-generality category involve students viewing and using models as tools for representing ideas and unknown phenomena. This interpretation of a Level 4 performance was easily identified in students' reflections about modeling. For example, Kingston defined a model as, "a picture of what you are thinking about a topic," and Jack wrote, "models don't need to actually look like the real thing they only need to explain the idea or nature of it as much as possible." We noticed that students tended to demonstrate this performance when they used models to reason about unknown phenomena.

We coded students' modeling performances as Level 4 when they used their models as a way to make sense of the relationship between different factors of their phenomena. For example, when one student was presented with anomalous data, she used her model as a resource to generate ideas that could explain the data, revising her conception of the original phenomenon. We currently conjecture that shifting among models was critical in supporting this practice. Students were able to generate new ideas because they were able to critique their initial diagrammatic and computational representations with data collected from their physical models. We found few examples of this level of practice; only about 25% of the students demonstrated Level 4 performances by the end of the project in either reflection or as they were constructing models, and no student demonstrated Level 4 performances across all conceptual and representational contexts. These data demonstrate, however, that middle school students are able to engage with Level 4 practices and epistemologies.

B. Audience

Initially, we conjectured that shifting among model types would support students in seeing models as tools. We assumed that students would intuitively recognize models as communicative, and we did not explicitly design to support this performance. During the project, we found that the collaborative nature of students' tasks supported them in using models for communication. Throughout the semester, students shifted between perceptions of models as tools for communication and for constructing knowledge, sometimes voicing both perspectives simultaneously. For example, Dylan's initial description of models indicated that she saw models as tools for teaching (Level 2). This perspective was typical for our students; in their Day 1 definitions of models, over 50% of the students wrote that models could be used to "show information" or "teach." Similarly, when prompted to describe the purpose of the diagrammatic models they constructed on Day 2, about 20% of students wrote that their models were intended to show information to others or teach others. On Day 2, Dylan wrote, "Models can be used to easily teach others of a certain relationship." This perspective is likely a result of how students were using their models. At this point in the project, students were showing their models to their peers, but they had not yet used their diagrammatic models to design physical models to test their ideas.

At the end of Cycle 1, Dylan described models as tools for constructing knowledge. On Day 13, Dylan wrote, "Models are used to make predictions about mechanisms and to see the relationship between two variables. Physical models can also be used to test the relationship between two specific variables to help understand your mechanism." In this description, Dylan focused on models as constructive tools and did not address their utility as communicative tools for teaching or collaboration, engaging at Level 4 of the Schwarz progression (models as constructive tools). Dylan's development in the audience category was representative of her peers; by Day 13, 52% of students described models as constructive tools, while only 9% described models as collaborative tools. These data suggest that physical modeling increased students' opportunities to perceive models as tools for constructing knowledge. While diagrammatic modeling had affordances for communicating with others, physical models were better suited to testing ideas. Overall, the percentage of students who described their models as collaborative and constructive increased in their written reflections throughout the semester. By the end of the project, roughly 25% of students expressed a belief that models are both collaborative and constructive in these reflections, and over 50% of the students identified models as either collaborative or constructive tools. Similarly, during the end-of-semester interviews, almost all students described models as a tool for learning and a tool for communication.

It is important to note, however, that when engaged in model construction, students' sense of purpose in terms of audience was more tenuous. Even when explicitly prompted to describe choices that they were making while modeling during Cycle 2, only about 50% of the students connected their choices to constructive or collaborative purposes. Of these students, roughly 50% described their models as tools for showing others information (Level 2), and approximately 55% described their models as tools for collaborating or for constructing knowledge (Level 3 and 4). As in the salience-generality category, no students exhibited Level 4 performances for the audience category across all conceptual and representational contexts. The cause of the gap between students' sense of audience in written reflections and their sense of audience during model construction is unclear. As we suggested in the salience-generality category above, it is possible that the gap was created by the difference between students' declarative knowledge and knowledge-in-practice. Students may also have perceived their own models as different from models in general, affecting their responses to these prompts. It is also likely that learning activities shaped students' beliefs and practices; for example, the task of writing may have provided greater affordances for considering audience and purpose, while the task of physical modeling encouraged students to focus on the material challenges of constructing knowledge. Exploring the affordances of these activities for engaging in high-level practice is important because it has implications for how students construct, use, and perceive their models.

C. Evidence

Initially, we conjectured that providing students with accessible, tangible content would support high-level practice in the evidence category, because students would have direct access to the phenomena they were studying rather than relying on external sources. Our data support this conjecture; in our classrooms, from the beginning of the semester to the end, the majority of the students demonstrated Level 3 conceptions of modeling in the evidence category. Our students' first modeling activity encouraged them to justify their models with general empirical evidence (Level 3). When students created their diagrammatic models on Day 2, they were asked to create a model based on observations from the garden. This activity discouraged the Level 1 perspective that no justification is needed for models, because students' models were explicitly grounded in their observations of the garden. The activity structure also reduced students' opportunities to adopt Level 2 justifications because (1) few students had prior knowledge about the garden, (2) students had no access to authority information sources like textbooks (because they were outdoors) or teachers (because Max and Ashlyn did not provide any content-related information), and (3) students attempted to represent all five garden beds in one image, discouraging them from creating case-specific representations. As a result, from the beginning of the project, this activity provided strong opportunities for students to engage with the Level 3 perspective that models are warranted by general empirical evidence.

D. Mechanistic-generative

Initially, we conjectured that physical and computational models would support students in using and perceiving their models as mechanistic and generative tools, because these models would emphasize cause-and-effect relationships and present data that resisted students' explanations of phenomena. Throughout the semester, we found that diagrammatic models also supported high-level practice. In this section, we describe the scaffolds that supported students in engaging with high-level practices in the mechanistic-generative category.

When we collected baseline data for diagrammatic modeling on Day 2, we noticed that while most students' models were descriptive, a few students identified patterns within their models. For example, in Meristem's model, she noted, "the thicker the layer of grass, the wetter the soil underneath." We conjecture that identifying such patterns is foundational for developing mechanisms because mechanisms explain why such patterns occur. We leveraged pattern identification to help students build predicted mechanisms (Level 3) by encouraging them to identify puzzling patterns and make predictions about causal explanations for those patterns. For example, prompting Meristem to explain the pattern that she identified led to mechanistic physical and diagrammatic models. In these models, she investigated mechanisms that regulate soil moisture, such as rate of evaporation at different depths of soil, rate of water absorption from roots, and differences in evaporation caused by shade from a variety of dead and alive plants.

We identified evidence of Level 4 beliefs and practices both in students' reflections about modeling and in the models that they created. Reflections were classified as Level 4 if they described models as generative predictive tools. For example, when prompted to describe the purpose of models on Day 32, Dylan wrote: "People use models to make predictions about a possible solution to a problem, make predictions about why things happen a certain way, and ask questions about the environment." Dylan's description was representative of a majority of the students. By the end of Cycle 3, over 60% of our students described models as tools for generating predictions and questions. We classified students' models as Level 4 if they included predictions or relevant unanswered questions. Approximately 45% of the students enacted this practice in their models by the end of Cycle 3, though no student engaged in this practice across all contexts.

E. Revision

Initially, we conjectured that thinking across model types would support students in engaging in revision practices as they encountered data that challenged their previous conceptions of their phenomena. Throughout the semester, however, we found that the collaborative nature of the project motivated students to engage in practices of revision for explanatory power as well. We currently conjecture that the structure of our activities prevented students from adopting Levels 1 and 2 practices in the revision category. Because we provided students with opportunities to revise their models within the first week of class, they did not believe that models were unchangeable. Because we did not provide them with access to textbooks and did not act as content experts, they could not rely on authority sources to revise their models during Cycle 1.

Yet, rather than making revisions rooted in empirical evidence (Level 3), we noticed that our students' initial revisions were made to increase their models' explanatory power (Level 4). For our students, revising models based on evidence was less accessible than improving them as mechanistic and predictive tools. Therefore, in this section, we explore challenges and supports for Level 3 practice as well as Level 4 practice in this category. Existing research suggests that responding to anomalous data is particularly challenging for both students and professional scientists. When faced with data that pushes back on their theories, students typically reinterpret or reject evidence in a way that does not require them to modify their existing theories (Chinn & Brewer, 1993; Kuhn, 2010). This response is amplified when students have not considered alternate theories that could explain their evidence. Our students' behavior was consistent with Chinn and Brewers' findings and with Kuhn's findings. When students' data contradicted their predicted mechanism, students tended to trust their reasoning over their evidence; they often assumed bias or errors in the evidence they collected rather than revising their models. Given that revision based on evidence is characterized as challenging for students in the literature, we believe that our students' difficulty with this performance is likely to be observed in other classrooms as well. Still, with appropriate scaffolds, students can revise models based on evidence, as demonstrated both by Schwarz and colleagues (2009) and by our students. By the end of the project, a majority of our students revised their models based on empirical evidence that they had collected and analyzed.

Significance

This paper contributes to ICLS's goal of helping researchers and practitioners unpack the complexity of learning and teaching in four ways, which we will explore in the following paragraphs. First, from a perspective of naïve epistemologies as fine-grained context-sensitive resources, the ideas that students draw on change in response to the classroom environment and students' interactions with other students and their teacher (Berland et al., 2015; Hammer & Elby, 2003). Our findings support this perspective, demonstrating that learning progressions for complex practices like modeling do not represent fixed linear pathways through which all students learn. Rather, a student may exhibit practices at multiple points along the progression at any given time across different conceptual and representational contexts.

Second, we have demonstrated that middle school students are able to engage in high-level modeling performances across categories of the learning progression. The examples documented for Level 4 performances provide insight into the nature of students' thinking, perspectives, capabilities, and limitations while engaging in high-level modeling practices.

Third, we described our conjectures about conceptual and representational contexts that supported and boot-strapped high-level performances. These findings align with existing research that proposes that circulating among mutually referential models encourages students to redefine and re-represent their ideas about the phenomena they are modeling (Lehrer et al., 2009).

Fourth, although learning progressions have traditionally been conceptualized as tools for designing aggregate curricular arcs (e.g., Gotwals & Alonzo, 2012), our students' enactments of modeling practices and beliefs did not follow the sequential trajectory of the learning progression. Instead, we found that the learning progression represented a range of modeling practices available to students, a valuable upper anchor for high-level performance, and an analytic framework for examining students' modeling beliefs and practices rather than a set of sequential levels that students move through linearly (Hammer & Sikorski, 2015).

References

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2015). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, *53*(7), 1082–1112.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and impli- cations for science instruction. *Review of Educational Research*, *63*(1), 1–49.

Fortus, D., Shwartz, Y., & Rosenfeld, S. (2016). High school students' meta-modeling knowledge. *Research in Science Education*, *46*(6), 787–810.

Gotwals, A. W., & Alonzo, A. C. (2012). *Learning progressions in science: Current challenges and future directions*. Rotterdam, The Netherlands: Sense Publishers.

Hammer, D., & Elby, A. (2003). Tapping epistemological resources for learning physics. *The Journal of the Learning Sciences*, *12*(1), 53–90.

Hammer, D., & Sikorski, T. R. (2015). Implications of complexity for research on learning progressions. *Science Education*, *99*(3), 424–431.

Kuhn, D. (2010). Teaching and learning science as argument. *Science Education*, *94*(5), 810–824.

Lehrer, R. (2009). Designing to develop disciplinary knowledge: Modeling natural systems. *American Psychologist*, *64*(8), 759– 771.

Louca, L. T., & Zacharia, Z. C. (2012). Modeling-based learning in science education: Cognitive, metacognitive, social, material and epistemological contributions. *Educational Review*, *64*(4), 471–492.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education*, *96*(6), 1071–1105.

National Research Council. (2012). A framework for K-12 science education. *A framework for K-12 science education: Practices, crosscutting concepts, core ideas*. Washington, DC: National Academies Press.

Östman, L., & Wickman, P.-O. (2014). A Pragmatic Approach on Epistemology, Teaching, and Learning. *Science Education*, *98*(3), 375–382.

Schwarz, C., Reiser, B. J., Acher, A., Kenyon, L., & Fortus, D. (2012). MoDeLS: Challenges in defining a learning progression for scientific modeling. In A. Alonzo & A. W. Gotwals (Eds.), *Learning progressions in science: Current challenges and future directions*. The Netherlands: SensePublishers, Rotterdam.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, 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*(6), 632–654.