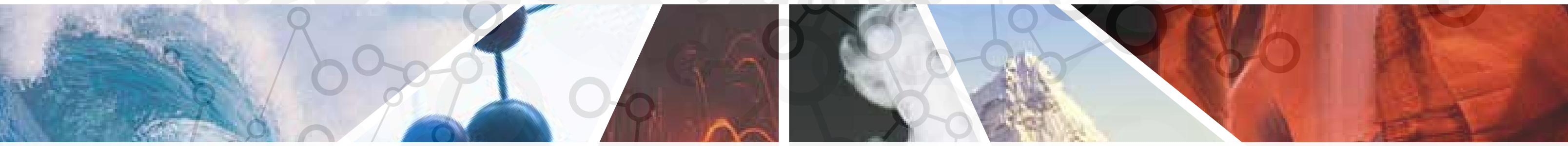
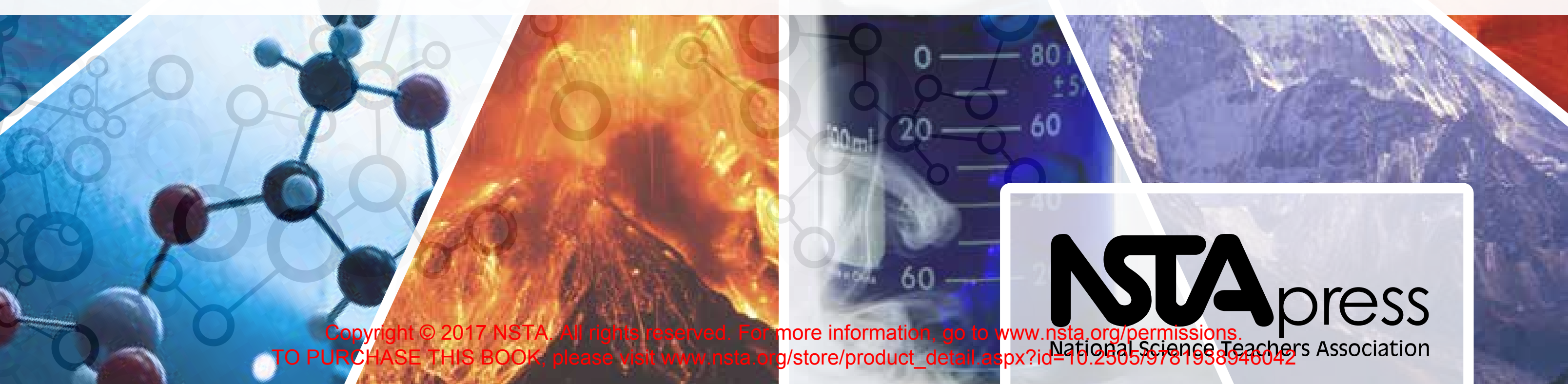
HELPING STUDENTS MAKE SENSE OF THE WORLD USING NEXT GENERATION SCIENCE AND ENGINEERING PRACTICES



Christina V. Schwarz • Cynthia Passmore • Brian J. Reiser
EDITORS



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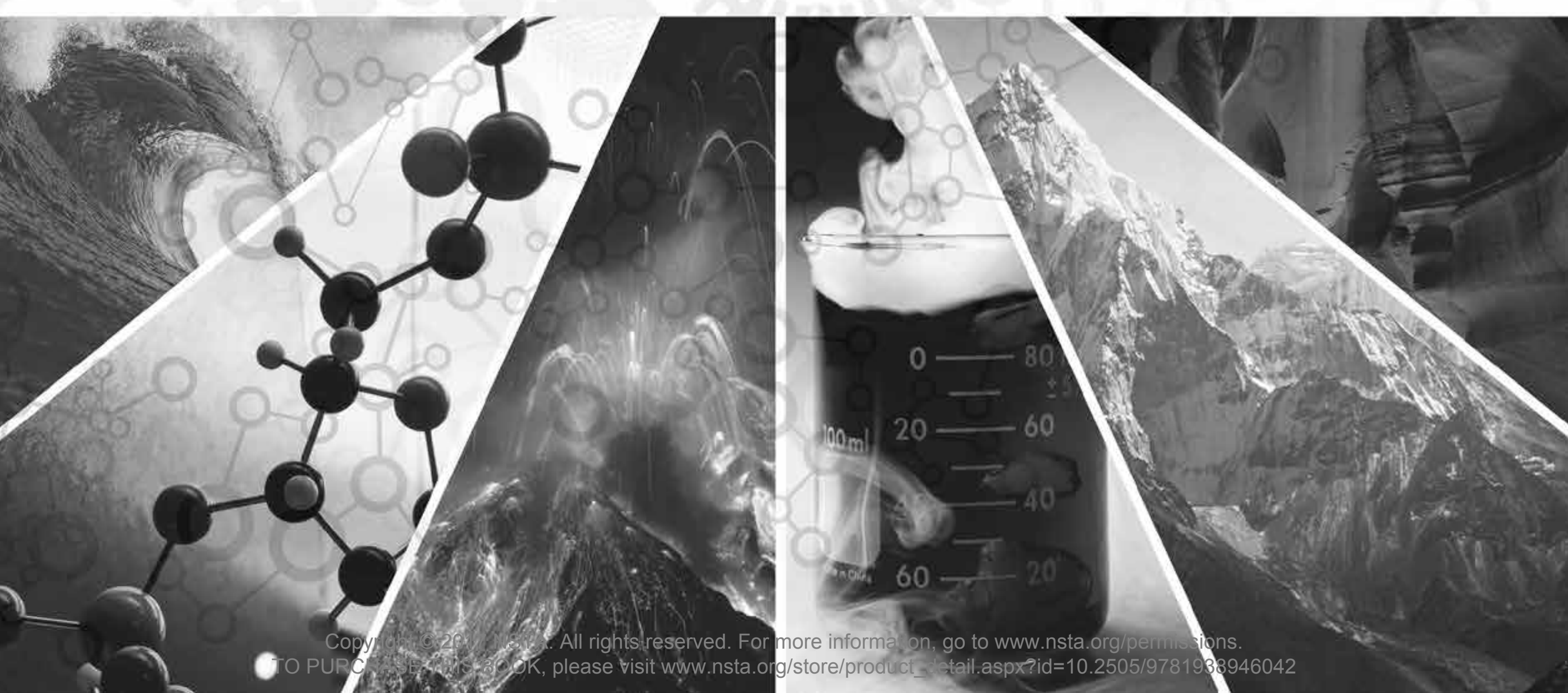

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SECTION 3

ABOUT THE EDITORS

Christina V. Schwarz is an associate professor of teacher education at Michigan State University (MSU). She teaches undergraduate and graduate courses in science and science education and has been the elementary science subject area leader for MSU's teacher preparation program for the past decade. She received her PhD in science, math, and technology education from the University of California at Berkeley and her undergraduate degree in Earth, atmospheric, and planetary science from the Massachusetts Institute of Technology. Her background includes conducting research in astronomy, designing curriculum materials for science learners, and working in classrooms with students and teachers. Her research primarily focuses on enabling students and teachers (preK–16) to understand and engage in scientific practices, particularly model-based scientific inquiry. She also works with beginning teachers to support and enhance their practices such as noticing and responding to scientific sense-making. She is the principal investigator for the National Science Foundation (NSF) grant Studying How Beginning Elementary Teachers Notice and Respond to Students' Scientific Sense-Making, the co-principal investigator for the NSF-funded project Supporting Scientific Practices in Elementary and Middle School Classrooms, and the principal investigator for the former Learning Progression for Scientific Modeling project. She is also co-principal investigator of the NSF-funded Head Start on Science preschool science project and was co-principal investigator for the Modeling Hydrological Systems in Elementary Science project. She has been an associate editor for the *Journal of Research in Science Teaching* and has published articles in journals such as *Cognition and Instruction*, *Journal of Research in Science Teaching*, *Journal for Science Teacher Education*, *Science and Children*, and *Science Education*. She has facilitated several National Science Teacher Association professional development webinars about the *Next Generation Science Standards* (*NGSS*) practices over the past few years.

Cynthia Passmore is a professor specializing in science education at the University of California, Davis, School of Education, where she instructs future science educators in the teacher education program. She completed her doctoral work at the University of Wisconsin, Madison. Before that, she was a high school science teacher in southern California and Wisconsin and served as a Peace Corps Volunteer in Malawi. Her research focuses on the role of models and modeling in student learning, curriculum design, and teacher professional development. She investigates model-based reasoning in a range of contexts and is particularly interested in understanding how the design of learning environments interacts with students' reasoning practices. In recent years, she has collaborated with groups of teachers to interpret and implement the vision of science education described in the *NGSS*. She has been the principal investigator of several large grants from the NSF and other agencies and foundations. Currently, she is working with collaborators to develop a year-long high school biology instructional resource package supporting the *NGSS*. She has coauthored papers on modeling in science education that have been published in journals such as the *International Journal of Science Education, Journal of Research in Science Teaching*, *School Science and Mathematics,* and *Science and Education*.

Brian J. Reiser is a professor of learning sciences at Northwestern University. He earned his PhD in cognitive science from Yale University. His current research examines how to make the scientific practices of argumentation, explanation, and modeling meaningful and effective for classroom teachers and students. He co-led the development of IQWST (Investigating and Questioning Our World Through Science and Technology), a three-year middle school curriculum that supports students in science practices to develop disciplinary core ideas. He is a member of the National Research Council's Board on Science Education. He has served on the National Research Council committees that authored *A Framework for K–12 Science Education* (which guided the development of the *NGSS*), *Developing Assessments for the Next Generation Science Standards,* and *Guide to Implementing the Next Generation Science Standards*. He has also worked with Achieve on tools to support implementation of the *NGSS*. He is currently collaborating with several state initiatives to design and provide professional development and create curriculum materials for K–12 teachers to support them in implementing in their classrooms the reforms in the *NGSS*.

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DEVELOPING AND USING MODELS

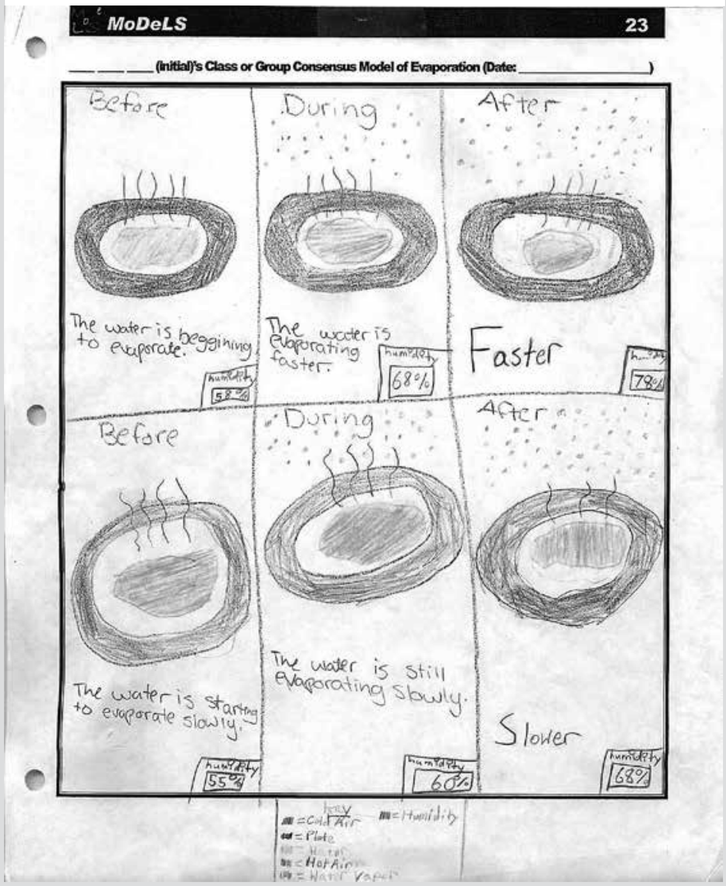
CYNTHIA PASSMORE, CHRISTINA V. SCHWARZ, AND JOCELYN MANKOWSKI

Fifth-grade students are busy working in small groups deciding how to show others in their class what they have figured out about how and why water evaporates. During their science lessons, these students have been trying to determine how a solar still works to clean dirty water. This phenomenon has led them to wonder about how water seems to move from one place in the apparatus to another. They've considered other cases of water seeming to "disappear," like when the water dries up on the playground after a rainstorm. They have spent the first part of the unit doing investigations around evaporation and modeling their ideas about how and why evaporation occurs.

The students talk to each other to decide what they want to include in their model diagram. Melanie suggests showing "before, during, and after"—or change over time—to illustrate the liquid disappearing. She also suggests showing "hot and cold," and Andrew agrees, saying that "hot water is more humid" and wants "to show that hot water evaporates fast and stuff." Andrew and Melanie argue about whether they should include the exact humidity measures in the air for the different temperatures of liquid, or whether they should use a general term like "slower" or "faster." They don't agree, so they compromise and do both. Finally, they decide that they need to include water vapor, as Melanie says, by "drawing dots in the air for water vapor in 'during' and 'after.' More in the 'after.'" Figure 6.1 (p. 110) shows student drawings of evaporation.

Each group in the class shares its consensus model, and the other students and the teacher offer ideas about strengths and weaknesses about each group's model. During this exchange, one student suggests that he likes that they have the exact percentage of humidity. The teacher reiterates that this is important because it "directly comes from the humidity detector investigations." So students are learning to use ideas and evidence from their investigations to inform their ideas about

Figure 6.1
Student drawings of water evaporating under different conditions



the process of how evaporation is occurring. They are still working through their ideas about why this is happening by building on some key elements of the model, such as water particles spreading out into the air in different amounts when there is hot water evaporating.

The students and teacher continue this work until they have come to some satisfactory ideas about how and why evaporation happens and how to represent that, and they continue their progress in the second part of the unit to figure out what else might be happening in the solar still, such as condensation, that helps them account for how water moves around in the solar still.

This vignette comes from a real fifth-grade classroom and helps illustrate one of several important activities involved in Developing and Using Models to make sense of the world. It addresses the performance expectation from 5-PS1-1, "Develop a model to describe that matter is made of particles too small to be seen," because students are developing and revising models to address the general phenomena of evaporation and condensation to explain why water disappears from the blacktop of their playground or appears on the outside of their cold drink (NGSS Lead States 2013, p. 43). In this case, they are figuring out the components of the model (what's important to include about the phenomena), the conditions under which the phenomena occur (the role of temperature and air), and how the components are related and interact over time (water particles moving and spreading out or clumping together under different temperature conditions) to help them account for how and why the phenomena occur in the world. The students and teacher are engaged in a process of model development and revision—making their ideas visible and testable to themselves and each other. They are evaluating and revising those models against data they have collected, against strategically introduced scientific ideas (from simulations), and against other students' ideas about what is going on and why to figure out how to best explain and predict similar phenomena. These are some of the essential aspects of engaging in the practice of scientific modeling.

Why Is the Modeling Practice Important?

> *Models serve the purpose of being a tool for thinking with, making predictions and making sense of experience. (NRC 2012, p. 56)*

From birth, humans are concerned with figuring out how the world around us works. Doing this helps us better predict what might happen to us in the future and gives us a better sense for how we are part of the world. As humans, we wonder about things; we conjure up ideas about how they work from a range of sources; we test those ideas; and we wonder, construct, and test some more. From the baby figuring out how adults react to certain facial movements, to the small child working out the rules of an imaginary game with his siblings, to the elementary student working out where the water comes from on the outside of her soda bottle, to the young adult coming to understand the ways force and motion are related to each other, we never stop trying to figure out how the world ticks. Sometimes we're happy that we can reliably predict the actions of our world, but often we want to know *why* something behaves the way it does. Knowing why can help us become even better at figuring out what will happen in the future. As we do this, we are searching for underlying reasons and mechanisms that help us make sense of our experience and of the world around us.

This innate drive to figure out and make sense of the world is at the core of the practice of modeling and forms the basis of the scientific enterprise. Like the baby working out some basic rules for physical objects by repeatedly dropping them from her high chair, the scientist is concerned with explaining and generalizing ideas about how and why the world operates the way it does. There is an important connection between the innate sense-making drive we all share and the formal scientific enterprise (Gopnik, Meltzoff, and Kuhl 1999) because both are harnessing the powerful learning mechanisms of the human mind.

To make progress on understanding how and why something happens, one has to consider the parts of the system and figure out how those parts are interconnected and related, and then develop ideas about how those relationships interact and lead to the initial observation or phenomenon. *A Framework for K–12 Science Education* (NRC 2012, pp. 56–57) reminds us that "scientists use models … to represent their current understanding of a system under study, to aid in the development of questions and explanations, and to communicate ideas to others."

In science, modeling forms the core of the intellectual work of scientists helping to organize and integrate theoretical and empirical work toward a fundamental goal of sense-making about phenomena. *In school,* modeling can function the same way and bring students into scientific practice in productive ways. It can lead to deep content understanding, and by participating in science, students may come to a more robust understanding of the scientific enterprise. Models as tools and modeling as a practice can help externalize and refine our ideas and thinking, which can bring students into the practice of *doing* science, not just hearing about it.

Because modeling is at the core of the intellectual work of science *and* it is intimately connected to our innate sense-making drive, it should lie at the core of the intellectual life of the science classroom. We like to think that modeling, or figuring out how certain aspects of the world work, is the action that brings coherence to the intellectual work in the classroom. When our goals as teachers center on working with our students to figure out and agree on a small set of ideas that can be used to explain a phenomenon in the world, then our classroom becomes a scientific community with the goal of advancing our knowledge about the world, and our students are put in the role of active knowledge builders in the learning environment.

What Is the Modeling Practice All About?

Why do we need a bridge between wondering about how something works and explaining how that thing works? It turns out that when we explain how something works, we are using, often implicitly, a set of ideas we have about the system or problem. Modeling is the process of making those ideas explicit. Recall the short vignette (pp. 10–12) about students learning near-Earth astronomy from Chapter 1. In this modeling unit (*http://ncisla.wceruw.org/muse*), students work through a series of phenomena like day and night, the direction of sunrise and sunset, moonrise, and phases. Through each cycle where they examine and wonder about a phenomenon, they work with props and each other to figure out what motions of the Earth and Moon cause that phenomenon. Students develop parts of the larger model by illustrating their ideas using words and diagrams. For example, in considering what causes the Sun to rise in the east and set in the west, the students must use the idea that the Earth rotates on its axis (established already by wondering about day and night) and add a particular direction of Earth spin. So, the ideas about what objects are relevant and what those objects are doing make up the model. In other words, the model, in this case, is the set of ideas about the Earth, Moon, and Sun, including their positions relative to each other, their motions, the relative distances between them, and so on, that can be used to explain why we see, for example, the Sun rising in the east and setting in the west. Thus, the model sits between the observed world (the phenomenon) and the explanation for what we see.

Models, as we are defining them here, are simply sets of ideas for how or why something in the world works the way it does. This definition focuses on a small set of ideas and the relationships between and among those ideas that allow us to explain what is happening in the world. From this simple definition, we can get at the full range of the modeling practice when we consider where those ideas come from, how they are shared and modified by a group working on a common problem, and how they are used to explain the problem at hand. **The essence of the Developing and Using Models practice is to figure out and use specific ideas about theoretical and actual objects and the relationships between them to account for the behavior of systems in the natural and designed world.**

What Are Models?

In science and in science education, the word *model* is used in a variety of ways. Sometimes a model is thought of as a typical or exceptional example of something (e.g., a model airplane that represents the features of the larger object) or something that can stand for something else (e.g., mouse models of humans for testing medicines). Sometimes, a model is thought of as an illustration of a phenomenon or a smaller copy of the phenomenon (e.g., stream table models). It is no wonder that the inclusion of Developing and Using Models among the list of eight practices in the *Framework* has caused a lot of confusion and some consternation among teachers.

To help clarify this practice, we introduce two big ideas about what a model is that may help you understand this practice a bit more deeply:

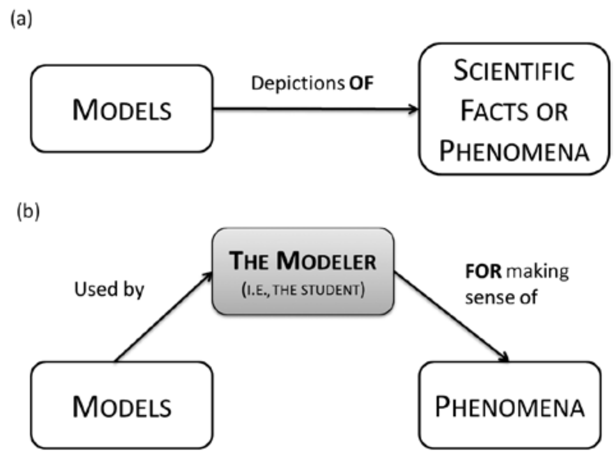
1. **Models are defined by how they are used.** Again, scientific models are sense-making tools that help us predict and explain the world. In engineering, models are used for analyzing, testing, and designing.

2. **Models are distinct from the representational forms they take.** They can take the form of diagrams, words, equations, or computer programs, as long as they embody ideas about how and why the phenomenon occurs or about components and relationships of the system being studied.

Okay, so what do we mean by that first point? Why is the *use* of models so important? Let's begin by making a distinction between two kinds of knowledge goals in the classroom. One kind of goal in the science classroom might be that students know *about* some scientific facts. Take, for example, the idea that the world is made up of tiny particles. As a teacher, I might have that "fact" as my learning target. Another way to think about this, though, is to consider what I want my students to be able to do with that fact. Do I merely want them to know *about* particles, or do I want my students to *reason with* the idea of particles to account for various phenomena in the world? Similarly, do I just want my students to know that the Moon orbits the Earth, or do I want them to be able to use that idea to reason through why we see phases of the Moon from Earth? This distinction between a fact-focused science class and a reasoning-focused science class is at the core of the first point about models being defined by how they are used.

We take the position that models are not merely depictions of science facts, but are tools for reasoning. This first point means that *we cannot really decide if something is or is not a model without also attending to how it is being used.* A model is used *in service of* making sense about an observable phenomenon in the world. Often, models are referred to as being of a system or phenomenon. For example, we sometimes talk about a model *of* the solar system. It is a convenient shorthand, but one that sometimes focuses us on the wrong relationship. Models in science are not merely *of* things in the world; rather, they are best thought of as tools *for* making sense of something in the world. So, the model, if it is truly a reasoning tool, is not *of* the solar system but something that can be used *for* explaining why, for example, we can only see Venus from Earth low in the sky just before and after sunrise and sunset. To be used as a reasoning tool, the model needs to be constructed *for* some sense-making purpose; it needs to be linked to a phenomenon. If something is merely shown to students or constructed for the purpose of depicting the parts of the system, but not how they interact in ways that help us understand why we see particular things in the world, then it is not truly operating as a model in the scientific sense. This is the distinction between learning science as sets of facts versus learning science as models that can be used to understand and explain our world. This is what the focus on Developing and Using Models in the *Framework* and the *NGSS* is all about (Figure 6.2).

Figure 6.2
The difference between models *of* and models *for*



In the science classroom, we want students to go beyond merely knowing about science facts. In diagram (a), the model is positioned as a depiction *of* something. In diagram (b), we keep the modeler in mind and consider what the model is being used *for*.

We want students to develop flexible and useful knowledge; knowledge that is a tool for understanding and interpreting the world, not just inert facts. Figure 6.2b shows how taking the modeler (the reasoner) into account helps us focus our attention on the purpose of the model and not just the relationship between the model and the phenomenon. This idea is developed more fully by Passmore, Gouvea, and Giere (2014).

The second point about models being distinct from their representational forms follows from the point about models as tools *for* reasoning. It is quite common to call a picture, drawing, physical replica, or mathematical equation *the model.* Take something like the foam ball representing the Moon in the near-Earth astronomy vignette (pp. 10–12). The ball itself is just a ball until it is used in the service of figuring out how the Moon moves around the Earth. Thus, it is not the ball that is the model here, but the *ideas* about what that thing is showing and how it helps us understand what the Moon looks like from Earth that makes it into a part of a model. We could just as easily represent that thing (the Moon) with a wadded-up piece of paper, a student's own body, or a circle drawn on the board. Each of these depictions could be representing the same underlying idea that this spherical object is moving around the Earth in a particular way. Thus, the representational form should not be confused with the model.

To make this distinction is not to underplay the importance of the representational aspects of the modeling practice. The format we use to share our ideas is very important, but in our work, we've found that sometimes if we don't make clear to students that the drawing or object is distinct from the underlying idea, then students can get distracted by representational concerns at the expense of the scientific ideas. To illustrate this point, imagine the group of students in the opening vignette (pp. 109–110) spending 10 minutes arguing about whether to use a green pen or a blue pen to draw their dots of water vapor. In this case, most likely the color of the depiction of water droplets would not be central to the model ideas, given that the key feature they are trying to represent with those dots has nothing to do with color. On the other hand, an extended conversation about which situation should have more dots would help them focus on the central ideas that they are working with in terms of relative abundance of water vapor under different conditions.

The key point here is not to get too concerned about what is or is not a model or what the best representation may be, although the representation can be an important instructional consideration. As educators, we must always ask ourselves about the purpose of any material activity in the classroom: What is the depiction, representation, or other item being used *for* in our classroom? If it is merely to show students the parts of a system and have them learn those parts as inert, declarative knowledge, then we are missing the point of the modeling practice. If, however, the objects are being used to represent sets of ideas for how a system is put together for the purpose of understanding how those parts and relationships interact to account for the phenomena we see in the world, then we are indeed modeling.

What Is *Not* Intended by the Modeling Practice

- Art projects that merely translate a two-dimensional image into a three-dimensional depiction or words into a drawing.
- Representations that only ask students to identify the parts of a system. These are not models unless they also depict relationships between the parts and can be used in an explanatory context.
- Students using a computer simulation to gather information without paying attention to underlying mechanisms—for example, tracking what conditions plants need to grow (light vs. no light, soil vs. no soil) or using a food web simulation that just shows who eats whom. Finding these kinds of patterns is important, but without attention to how and why the patterns exist, this kind of work falls short of the modeling practice.

What Is Modeling?

So, if a model is something used for making sense of phenomena and something that can be represented in a variety of ways, then what is the modeling practice? There are a number of ways to engage in modeling. We find it useful to distinguish two types of modeling. Broadly, we think about two main ways we use models in science: We think *about* models, and we think *with* models.

To think *about* the model is to do the intellectual work of deciding what goes into it and what doesn't, and how to portray those ideas to others. There are some fairly useful ways to think about models in the classroom. To help students think about models, students engaging in the modeling practice should be developing and revising scientific ideas in an effort to understand how or why something happens in the world. Overall, the practice of modeling should involve students in *developing* a model that embodies aspects of a theory and evidence, *evaluating* that model against empirical evidence and theory, and *revising* that model to better meet the goals of explaining and predicting. When students are doing these things, we see them wondering about what goes into their model. They must examine the component parts of a system and figure out what the key parts are and how they are related to each other. To come back to the near-Earth astronomy example, students were thinking *about* the model when they were deciding what objects were relevant and how to describe what those objects were doing (spinning, orbiting, or staying still with regard to another object). In the opening vignette in this chapter (pp. 109–110), students are thinking *about* the model when they are deciding on the importance of the humidity data.

A goal of science education should also be to help students "think with" models. To do that, students need to *use or apply* models to predict and explain phenomena in particular ways. This is sometimes called "model-based reasoning." So, for example, the students developing and revising their models of the Earth–Moon–Sun system were using their models when they were predicting and explaining what causes the Moon phases. By the time they wondered about that phenomenon, they had all the necessary pieces in their model. Their model stipulated that the Moon orbited the Earth about one time per month. To explain phases, they had to use that idea in their model. In this chapter's opening vignette, the goal was for students to *use* their models about evaporation and condensation to explain the functioning of the solar still. They began by wondering about that apparatus and how it worked, they spent several days in class modeling the underlying processes that govern it, and ultimately they used the resulting models to fully account for how the water moves around in the solar still.

The practice of scientific modeling and engineering modeling involves these iterative cycles of development, testing, and use—guided by the goals of sense-making. These cycles of developing, testing, and revising are very important for learners to better understand how the practice can help them develop and refine their own understanding of the world.

In addition to the iterative cycles of model development and revision, there are important criteria for models and modeling. Science typically aims to develop a model that is accurate with respect to predicting and explaining phenomena and that can provide some insights into how and *why* the phenomenon happens—by giving some sort of mechanism for why the phenomenon happens. It is also important that models be general enough to be applicable to other phenomena and useful for the modelers. In engineering, the model needs to help the developers test and refine their systems, to solve the problem they aim to solve. (For more on the practices as they play out in engineering contexts, see Chapter 13, p. 283.)

Each class can develop its own knowledge and norms about modeling. There is research showing that these are very important for helping students move beyond producing pretty pictures or three-dimensional representations toward using the models as sense-making tools. It is also helpful to talk with the class explicitly about goals and how we are going to meet them as we engage in modeling. This helps some students better understand what they need to do and why.

It is essential that students be given the opportunity to do both kinds of reasoning we have described here. They need to be engaged in thinking *about* the model—what goes into it and why. Having the teacher tell them about the model, or show it to them and then have them use it, only gets them so far. They need to have a chance to think in generative ways about what the model is meant to do and how it might be constructed to do those things. So, although model use (or thinking *with* the model) is important, it is not the only aspect of the modeling practice. Thinking *about* the model by developing it and revising it can help students gain more ownership of the ideas and can help them see clearly how the theoretical ideas being developed in class connect to the phenomenon under study. It might feel more efficient to just skip the model-generation part of the lesson, but doing so diminishes the power of this practice and makes it less likely to be linked to sense-making.

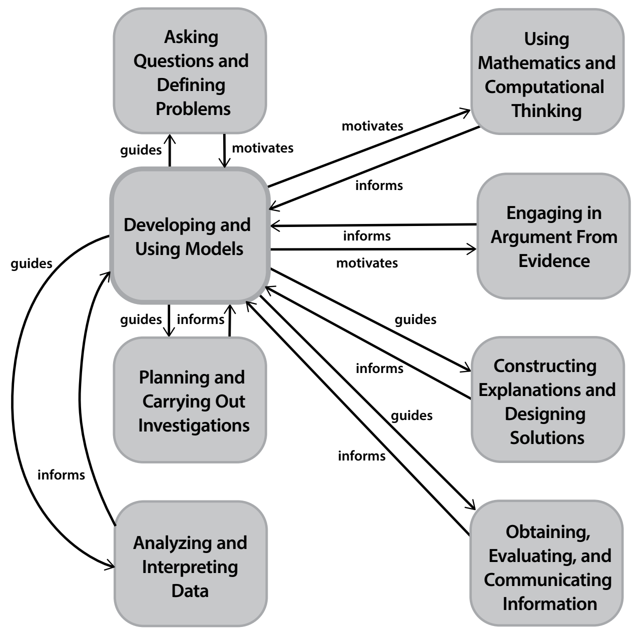
How Does the Modeling Practice Relate to the Other Practices?

Modeling can be an anchor practice that motivates, guides, and informs the other practices and brings them into a broader approach to productive sense-making. As we work to develop models for what is happening in the world on a mechanistic or causal level, we will seamlessly engage in the full range of other scientific practices highlighted in the *Framework* and the *NGSS.* Any modeling endeavor is inherently linked to some phenomenon in the natural world and therefore can and should be connected to a question or set of questions. In our work with teachers, we often help them make this link by asking them to work with kids to clarify exactly what it is they are trying to figure out. In the opening vignette, the students are presented with the phenomenon of the solar still and are led to wonder about how the water moves from one place in the apparatus to another. This wondering is best made explicit through asking questions such as these: Where did the water in the upper receptacle come from? Is it pure water, or did some of the dirt from the lower receptacle come with it? How did the water move? Why does it need to be in the Sun to work? These questions then imply a range of investigations that will generate data that need to be analyzed. As we plan investigations, we use our beginning models to guide us and help us interpret our results. Likewise, the results of the investigations may lead us to add to or modify our models. Throughout this process we must engage with other learners or investigators to check in about what we think we are figuring out and why we think those ideas are useful. These comparisons, elaborations, and justifications are at the heart of the argumentation practice. Often in science one way to depict the relationships within a model leads us to use some mathematics. This happens in physics a lot but can be salient in other disciplines as well. Consider how we might model relationships among the number of gas particles, the space in which they are contained, and the frequency of hits on the side of the container (i.e., the idea of pressure). Using a mathematical relationship might be a powerful way to depict these ideas. The aim of all of this work is to account for how something works in the world, and thus if we are truly engaged in Developing and Using Models, then we must attend to explanations. An explanation is the ultimate use of a model (more on this below). Throughout every aspect of this work, students must be engaged in the communication practice. Science is a social process, and to engage in it requires communication as we present and work through different ideas as a community.

Thus, we see the practice of Developing and Using Models as inexorably entwined with the other practices. You cannot be modeling without asking questions, investigating, arguing, communicating, and explaining. To summarize, we see some of the central connections as depicted in Figure 6.3 (p. 120).

One particular connection we've made earlier probably deserves some extra attention, and that is the relationship between models and explanations. This can get a bit sticky. Indeed, you might hear the phrase "explanatory model" or "model-based explanation" in science. So, are explanations and models really just the same thing? We think models are different from explanations. The distinction might seem a bit theoretical to some, but we think it is important to understand. The model is the set of ideas that are used in an explanation for some phenomenon, and the explanation is the product of playing out the model in a particular situation to account for that phenomenon. For example, to return to the Earth–Moon–Sun astronomy example, we would say that the ideas in the model are about the relative positions of the celestial bodies. In other words, the model contains

Figure 6.3
The relationship between modeling and other *NGSS* practices



- Models help identify questions and predict answers.
- Models help point to empirical investigations.
- Models are the filter through which data are interpreted.
- Models are revised and applied to "answer" or explain, predict, and solve.
- We use mathematics to formulate some models and mathematical reasoning to evaluate models.
- Argumentation is involved in both developing and evaluating models.
- Models hold and organize relevant information and become the focus of communicating ideas.

theoretical ideas, such as that the Earth is spinning on its axis once every 24 hours, or the Moon orbits the Earth in the same direction that Earth spins. Depending on the phenomenon we are trying to explain, we will draw on elements of the model and specific features of the phenomenon. If we are trying to account for the phenomenon of Moon phases, simply stating the relevant model feature (the Moon orbits the Earth approximately one time per 28 days) is not enough. On its own, this does not actually explain anything. Instead, to craft an explanation for this phenomenon, one would have to *coordinate* the model with the phenomenon itself to generate the explanation. An explanation would be something like the following:

> When we look at the Moon from Earth, *we only see half of it and at any given time* <u>only half of the Moon is illuminated by the Sun. Because the Moon orbits the Earth once every 28 days,</u> the position of the Moon with respect to the Sun and Earth changes throughout the month, and therefore the *part of the illuminated half that we can see from Earth changes.* Sometimes *we can see the entire illuminated part, which we call a full Moon, and sometimes the entire illuminated half is facing away from us, which we call a new Moon.* Throughout the month, the portion of the lit half of the Moon that we can see from Earth gradually changes from one day to the <u>next as the Moon orbits the Earth,</u> and thus we see *the Moon go through phases* from our perspective on Earth.

In this explanation, you can see that there is text that refers to the specifics of the phenomenon and text that refers to the model woven together. In the explanation above, we have italicized the parts specific to the phenomenon and underlined those that state the model ideas. Text that is neither italicized nor underlined is the "glue" that holds it all together to form a coherent explanation.

Another way to think of this is to think of the model as the underlying rules of a system and an explanation as a description of how those rules play out in particular ways. Let's use a nonscience example to illustrate. I might know the rules of baseball, but to explain to someone what happens during a particular play in the game, I would have to coordinate the ideas about the rules with descriptions of what actually happened. Imagine that there is a player on second base and the batter hits a pop fly, which is caught by the center fielder. The runner on second took off for third right when the batter made contact; after catching the ball, the center fielder then throws it to the second baseman; and the runner is called out. If I don't know the rules of baseball, this play would mystify me. If my companion watching the game with me merely stated the rule that "a fly ball caught in the air is an out, and the runner cannot advance," I would be no less confused. This is like telling me only the relevant piece of the model. To actually *explain* why the runner was out, my companion would have to help me see why that rule was relevant to the situation. So, knowing the rule is critically important in this scenario, but having the rule as inert knowledge would do a baseball fan little good if she could not think through how that rule applied in particular situations. Likewise, in the science classroom students must come to understand the models, but they must also be given opportunities to apply those models to account for phenomena in the world. Ultimately, both models and explanations are critical for sense-making in science, which is why they play such important roles in the *Framework* and the *NGSS.*

Relationship Between Modeling and Mathematics and Computational Thinking

There is a special connection between the Using Mathematics and Computational Thinking practice and the Developing and Using Models practice. As illustrated in this chapter and in Chapter 9 (p. 181), there can be a great deal of overlap in the intellectual work of students (and scientists!) when they engage in these two practices. The essence of the modeling practice is to develop and use specific ideas about theoretical and actual objects and the relationships between and among them to account for the behavior of systems in the natural and designed world. Very often, those relationships can be specified in mathematical or computational terms, so the two practices can become completely intertwined. Mathematical relationships and computational processes are often powerful ways to represent, share, and test our ideas about how and why a phenomenon happens. It is important to note, however, that not all models can be expressed mathematically or computationally, and not all mathematical expressions or simulations are necessarily models. To reiterate a point in this chapter, it depends very much on how the student thinks about and uses mathematical or computational representations.

What Does the Developing and Using Models Practice Look Like When It Happens in the Classroom?

What can modeling can look like in the classroom? We will share two cases of classroom modeling—one from the upper elementary or middle school level in physical science and the other from the secondary level in biology. Both illustrate ways in which students are positioned as knowledge developers trying to make sense of the world—by thinking about and thinking with models.

FIFTH-GRADE EVAPORATION AND CONDENSATION CASE

This case elaborates the example illustrated at the beginning of this chapter (pp. 109–110). (For a description of the unit, see Kenyon, Schwarz, and Hug 2008). The fifth-grade class was studying what happens to the liquid in a solar still. The teachers and students were addressing 5-PS1-1, "Develop a model to describe that matter is made of particles too small to be seen."

Throughout a six- to eight-week time frame, the unit followed a curricular sequence that asked students to engage in cycles of constructing and revising their models over time to better answer the question about what happens to the liquid and why. This sequence is described in Baek et al. (2011) in greater depth. The curriculum followed a sequence that supported this cycle of revision in the following ways:

1. Teachers pose a central question about the phenomenon of water seeming to disappear and appear in different places throughout the solar still apparatus.
2. Teachers ask the students to develop the initial diagrammatic model of evaporation (or condensation) based on what they know so far to explain how and why the water disappears and appears in the phenomenon.
3. Teachers support students at conducting empirical investigations about the phenomenon, and students can use this information in later model revision.
4. Teachers and students interact with computer simulations and theoretical ideas with model revision and evaluation.
5. Student groups and teachers work together to develop a consensus model for why and how the phenomenon occurs.
6. Students apply their models to other related phenomena.
7. The sequence is repeated with condensation.

Let's unpack this sequence to see what this looked like in this case: Teachers and students started the unit with a question about some phenomena. In this case, the anchoring phenomenon was water movement in the solar still and the central question was "Would you drink the liquid in the bottle cap from a solar still?" (See Figure 6.4.)

Figure 6.4
Diagram of the solar still apparatus

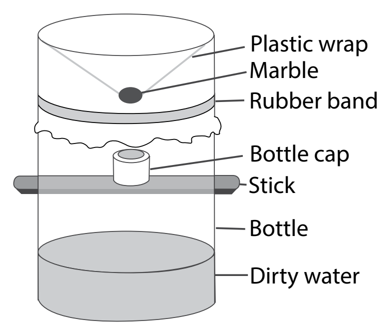
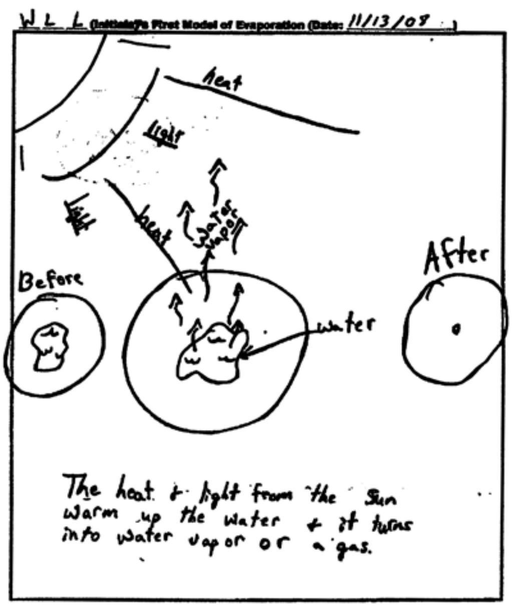


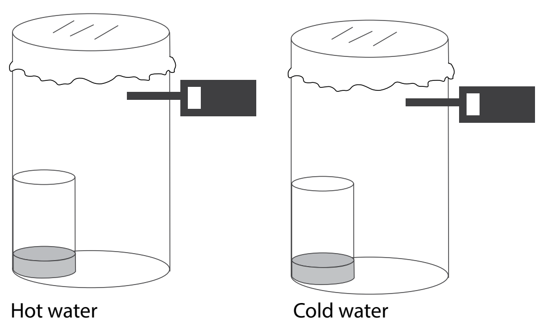
Figure 6.5
A student drawing of what happens when a puddle dries up



Because students cannot drink the liquid to test it, ideas needed to be developed about the invisible processes involved. The teacher asked the students to develop an initial model of what might be happening to the dirty water at the bottom next to the air in the container (evaporation). One way to start modeling is to simplify this situation and ask students what happens in any phenomenon in which water seems to appear and disappear—such as puddles on the playground. Students wrote and drew their initial ideas about the answer to that question, such as the one illustrated in Figure 6.5, in which a student shows what happens when a puddle dries up. This is a fine answer for most classrooms, except that it doesn't explain in much detail exactly how or why this happens or address the performance expectation for the grade at this point.

How might a classroom move from here? How might learners figure out if this is accurate or how it happens? Since there are likely to be alternative views of how evaporation happens under what conditions, it is useful to test some of the most common ideas using investigations. Measuring water vapor is very difficult under many circumstances, but there are some ways to do it with some help from old and new technology. One way is to mark a water level line in an open cup and closed cup to see how the water levels change over time. This helps test whether the water actually leaves the container when it looks like it disappears. Another is to measure the weight of the water as it evaporates. With a very sensitive scale, one can actually "see" the weight getting lighter. In addition, cobalt chloride strips, which change color when they detect water vapor in the air, can be used to test for evaporation. Students can investigate this next to a humidifier. Finally, digital probes with humidity detectors are extremely useful for collecting real-time water vapor data. They can measure the amount of water vapor in the air under various conditions (e.g., hot water, cold water, larger surface area, and smaller surface area). Figure 6.6 shows the use of probes.

Figure 6.6
Probes measuring water vapor



In this scenario, students and the teachers used stations where they collected the information and looked at the patterns they saw to inform their models. They observed that the cold water still evaporated even though there was not a direct heat source. It just happened slower. They also found that the water didn't disappear; it just changed location from the container with liquid to the air.

Figure 6.7
Student working on model revision

At this point, students went back and revised their models to consider what they had just found. The evidence pointed to some clues as to how water movement occurred, but they still did not have an answer for exactly why it was happening. Figure 6.7 shows an example of a student's revised model.

To help students find out more about how and why the water was moving, the teacher introduced some scientific information. Some of this information involved a theory that the teacher explained to the students: "Water is made of tinier parts of water (water droplets), and the tinier parts are again made of even tinier parts. (We can call them 'bits of water.') Those tiny bits are too small to see with our eyes. When the tiny, tiny bits are next to the air, they spread out into the air. They are so small that you can't see them, and so small that they float. When water does this, it has turned into a gas called water vapor. This process is called evaporation." In addition to this explanation, the teacher and students used a computer simulation software called Molecular Workbench, from the Concord Consortium, and asked students to interact with it (as shown in Figure 6.8). In this simulation, students can begin to visualize what these tiny bits of water might be doing as they move between the liquid and gas phases in the test tube. (See *www.concord.org/molecularworkbench.*)

Figure 6.8
Screenshot of the Concord Consortium's Molecular Workbench

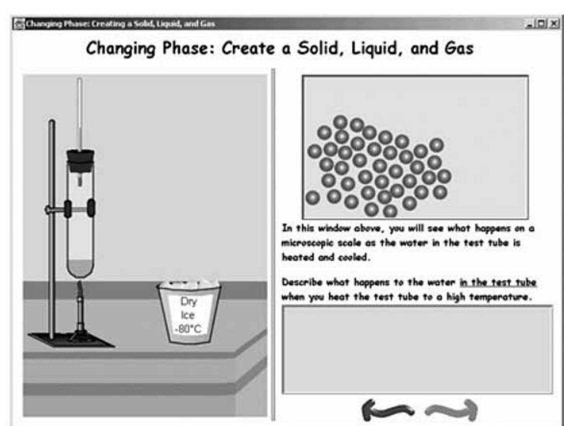
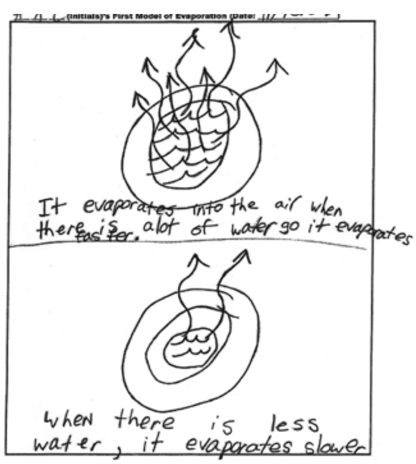
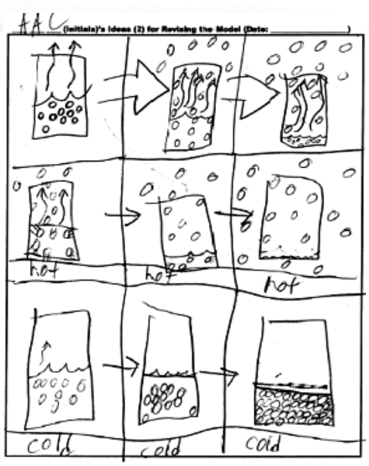


Figure 6.9
Initial and revised models after working with the Molecular Workbench simulation

(a)



(b)



Once the students visualized those bits of water moving in the simulation, students revised their models again and addressed the phenomenon using ideas about the particle nature of matter. Figure 6.9 shows a student's initial model and the model right after the introduction to idea of water bits in the unit.

PEER COMPARISON AND EVALUATION TO CONSTRUCT A CONSENSUS MODEL

Finally, the classroom worked together to create a consensus model of evaporation and, later, another for condensation. While some teachers ask their students to create consensus models in small groups, others do so as an entire class. The process of negotiating ideas in consensus models is sometimes challenging, though critical for helping students understand that the model needs to be consistent with the evidence they collected and needs to predict and explain the phenomenon. Here is how one small group in class negotiated its evaporation consensus model—within a classroom where the teacher emphasized the importance of showing how and why the phenomenon happens in the model and that it can be used for reasoning about other phenomena in the world:

Ben: "Should we label right here and write "no direct heat source?"

Teacher: "Sure, Ben. Your air molecules are too close together. Remember in the simulation how they spread out?"

Ben: "Yeah, but we don't have that much room. …"

Teacher: "Okay, we can make a note there that they eventually spread out."

Jack: "Why don't we just put an explanation on it?"

Ben: "Well, this is all the explanation."

Jack: "All right. You need to explain that a little bit more."

Teacher: "We have to explain it didn't seep through the cup, if someone asked that. Our model cannot explain that."

Jack: "Well, does this explain how paint dries?"

Teacher: "Yes, the water molecules are leaving. This explains how nail polish dries. It also explains how you can smell stuff, because molecules go away carrying scent."

After the final consensus model in the unit, the students then applied this to the solar still to determine where the water came and went. In that sense, they used their models to create an explanation of the solar still.

HIGH SCHOOL EVOLUTION CASE

A group of 36 ninth- and tenth-grade students entered the room. It was the third week of school, and the teacher had worked with the students to build a classroom community in which the students expected that they would be asked to wonder about some phenomenon in the natural world and seek to figure out how it works. This day was no different. Ms. C began by asking the students to recall the "big, huge driving question" about biology that they had developed and posted on the wall based on previous lessons. Amber raised her hand and said, "Well, I think what we decided yesterday is that we are trying to figure out how all living things can be so crazy different from each other and at the same time they have a lot in common, too!" Other students nodded their heads, and Ms. C pointed out the piece of poster board she had tacked up toward the back of the room with their "big, huge driving question" written on it.

Ms. C began the main lesson by saying, "So, today we are going to get started on figuring some of this out by looking at some organisms and what happened to them over time." She then shared three stories about change over time: She showed pictures and briefly told the story of peppered moth distribution in England in the 1800s; she told a story about antibiotic resistance; and she showed images and presented information about a population of some finches on the Galapagos Islands that had a measurable change in average bill depth across the population over a three-year period. At the end of her presentations, she asked the students to wonder about these three stories, consider the big driving question they had discussed before, and brainstorm some questions about the commonalities in the scenarios they just discussed. After about 10 minutes of pair discussions and whole-class conversation, they arrived at a consensus question: "How do populations change in their characteristics over time?" At this point, Ms. C told the students that to begin to explore this question, they would need look at data from one of these populations in depth, the Galapagos finches. She divided the students into groups of nine.

"I'm going to pass out a data set to each group. Look at the screen—I've got a little bit of introductory information for you before we get started." From here, she showed a few slides that illustrated where the Galapagos Islands are located, and she told them that the data they would be receiving were gathered by a couple of scientists named the Grants over several years of careful observation of some birds, the medium ground finch, that live on the island of Daphne Major.

Ms. C continued: "Your task is to look over the data and first get a sense of what happened to this population of finches over time on the island. What was the specific change in the population? Once you are clear about that, look over the other data about feeding behavior, rainfall, and survivorship and see what you can piece together about what may have caused the change. Use your whiteboards and the timeline I've provided to collect your initial ideas."

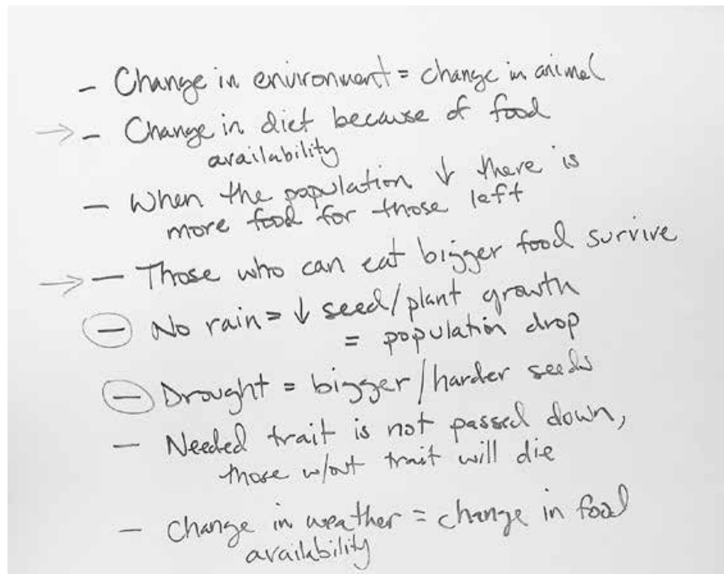
The students got to work and spent the remainder of the class period examining the data and discussing what happened to the finches and why. The following day, the students entered the room ready to continue working with the finch data. They pulled out their smartphones to look at the images they had snapped the day before of their whiteboards, and they took out their paper timelines. Ms. C told them that their task in the next 20 minutes was to take their ideas from yesterday and weave them into a "how and why" story about the change in the average finch beak size from 1976 to 1978. They wrote their first drafts on their whiteboards, and then, once they were satisfied with the stories, they transferred them onto butcher paper. Once all nine groups had their stories put together, they posted them around the room.

Ms. C said, "Okay, now we need to take a look. We are going to do a gallery walk and examine one another's work. We are looking for both commonalities and differences. Ultimately, our task is going to be to figure out some of the things that might be applicable beyond just the finches. What might be some rules that govern a change in the distribution of a trait over time? First, let's take a look at commonalities and differences. Take your assignment sheet and look at four posters besides your own, and write down the things you see across them that seem to be common and things that are unique to one or two."

The students stood up and examined other posters. The room was mostly quiet as students looked over the different posters around the room and wrote down their ideas. This took the rest of the period, and just before the bell rang, Ms. C. asked the students to come in the following day with a first draft of some of the general characteristics they saw in the posters.

The following day, after some introductory comments, Ms. C had the students return to their groups with their homework ideas and work together to come up with a list of the main ideas around how and why the finches changed over time. They shared their ideas and refined them, using the whiteboards at each table. Ms. C then called the group together to gather their ideas. She wrote notes on the board as the groups gave her one or more of the statements they had developed. After about 10 minutes, she had a list, as shown in Figure 6.10.

Figure 6.10
Notes written on the board after group discussion



"So, as I look at this list, I see some things that are specific to the finches and some things that we might think of as more general. Can we make the whole list into a general one that we might be able to use to explain any population change over time? Take a moment and write some ideas in your notebook about how to make some of these ideas that are specific to the finches into more general statements about the conditions that would lead to change over time for some other population."

She continued, "Let me give you an example. Here it says there was a drought on the islands. What might be a more general way to say that? Remember the story about the peppered moths? What happened there?"

Gina said, "There was a lot of pollution?"

Ms. C replied, "Yes, pollution, lack of rainfall—how might we say something about that more generally?"

Alex said, "Well, they both have to do with the environment, is that what you mean?"

"That's it, what happened to the environment—it was pollution-free and there was a certain amount of rainfall that was normal, so what would we say happened to the environment in each of these cases?"

Min said, "It changed?"

Ms. C replied, "What do you all think, does that capture it? Could we say something about a change in the environment instead of just saying change in rainfall?" Several students nodded their heads and muttered agreement. "Okay, so see what you can do with the rest of this list to make it more general like that."

The students worked with their partners for about five minutes, and after that, Ms. C ended the class period by getting their revised statements up in a column next to the original list.

The following day, the students came in and began a more in-depth exploration of each of the ideas they had put forward as part of the model. Ms. C had them go through a series of activities that allowed them to investigate the importance of variation, competition for resources, and heritability. They then decided on a final form of the idea for their developing model of natural selection (see Passmore et al. 2013).

After several days, they had one final opportunity to refine and apply their complete model to another phenomenon. This scenario is based on actual classroom events and addresses the *NGSS* performance expectations HS-LS4-2 and HS-LS4-4.

TAKEAWAY POINTS ABOUT THE CASES

Each case illustrates a general instructional sequence that helps support sense-making about phenomena through modeling. There are several important aspects in the cases examined in this chapter:

- Engaging in modeling is a multiday endeavor. It takes time to ask students to represent and revise their ideas. But, it's worth it! Students learn and make sense of phenomena in much more powerful ways that may stay with them longer. They also gain a richer and more personal connection with science.
- It is important that the modeling work in the classroom is always connected to a phenomenon and clear questions about it, so that students can track their progress on understanding how and why the phenomenon behaves the way it does.
- Modeling is contextualized and interacts with all the other practices for the goal of making sense of phenomena. You cannot separate the practices from one another in any meaningful way.
- Modeling is a social practice. At its best, it involves exchanging ideas, opinions, theories, and critiques with others—especially peers with the goal of advancing those ideas. This is not always easy, but it's worth teaching and attending to in the classroom. There are several aspects of the practice of scientific modeling that are critical social processes, important for advancing students' sense-making. Those include evaluating and revising models—and developing and using consensus models with a class. Each of these modeling practices requires that learners engage in argumentation about such things as the features of models and the application of models while engaged in doing things like comparing and contrasting models. (See Cheng and Brown 2015 for modeling criteria; another example is in Forbes et al. 2015.)

How Can We Work Toward Equity With Regard to Modeling?

We think that centering classrooms on participating in scientific and engineering practices in general, and modeling in particular, can create more equitable spaces for students. Engaging in the modeling practice is to engage in a very personal, though socially negotiated, process. No longer is the authority for ideas vested solely in the teacher. Instead, the classroom is centered on the collective endeavor of making sense of the world, our world, the one we experience every day. We must remember that all students have relevant life experiences to bring to this work. It is then our job to create space for those experiences to be seen as productive resources from which to build. Engaging students as the generators and evaluators of knowledge can be a very important way to help them see themselves as agents of their own learning. Education is not something that should be done to kids. We must work to find ways to bring them into the process, and engaging them in modeling is one powerful way to do so.

At the same time, it is important to note that modeling might take different forms for different cultures and students. For example, it is important to help students relate abstracted representations (particularly classic scientific models) with story-telling narratives and other ways of figuring out how and why the world works the way it does. It is important to leverage students' resources in the models and build on the ones that help students' sense-making—rather than shutting down this sense-making process. This can be tricky, particularly when engaged in wanting to converge toward particular ideas in science such as in a consensus model. It is important at that time to really decide what ideas and reasoning are critical for students to be able to leverage later, and which ones are likely to resolve on their own—or to be unimportant to subsequent learning. Please refer to Chapter 3 (p. 33) for more ideas about these kinds of connections.

How Can I Support and Assess Developing and Using Models in My Classroom?

To focus and clarify exactly what you will be doing with students in a modeling unit, you need to consider the phenomenon you will be centering your instruction around and the specific question(s) about that phenomenon that will focus the modeling. As the teacher, you have to be clear about the model you are aiming toward; the ways that the model can be represented; and how you will guide students in developing, testing, revising, and extending these ideas. This may seem daunting at first, but once you do it a few times, it can become more straightforward.

One important aspect of supporting learners in the modeling practice is to make sure that the developing ideas are written down and accessible as you move with your students through the unit. Information and ideas should be recorded by individual students in their notebooks, and we have found that displaying key ideas on a wall in the classroom keeps everyone grounded and makes the models accessible and useful. The teachers with whom we work often use summary tables like the one described in "The Modeling Toolkit" (Windschitl and Thompson 2013).

Assessment in the modeling classroom can be a challenge at first, but we've found that when students are truly engaged in this practice, there are many opportunities to see their thinking. These opportunities can lead to both formative and summative assessment opportunities. Consider the drawings and demonstrations that students create as part of their modeling endeavors as artifacts that can be used for assessment purposes.

Perhaps you are concerned about the fact that many of these artifacts may have been created by a group, making evaluations of individuals difficult to make. We've seen teachers employ some very creative ways to address this. Some teachers require an individual written product in addition to the group product, perhaps a quick write-up at the beginning of class or a short homework assignment. Another strategy is to provide mini-challenges for model use sprinkled throughout the unit that function like quizzes. For example, in the Earth–Moon–Sun astronomy unit, each time the students agreed on an addition to their model, the teacher would present them with a few thought scenarios to write about. In these scenarios, they were typically asked to think through an alternative to the model idea they had just come up with. So, if they had just figured out as a class that the Moon orbited the Earth once every 28 days or so, then the teacher might ask them to individually write about what we would see from the Earth if the Moon orbited twice as fast. Or, in the case of the solar still investigation, the teacher could ask the students to think through what would happen if the apparatus were put in a giant see-though freezer outside on a sunny day. These kinds of opportunities are important for students to solidify their own understanding and make it clear to the teacher whether the students are really tracking the ideas or merely parroting them.

How Do I Get Started With Modeling?

To get started with the practice of Developing and Using Models, we encourage you to make sure that you are viewing learners as developers and evaluators of knowledge, not just consumers. All disciplines in science have at their core a central activity of *making sense* of our world and why things work the way they do. School should *engage* students in doing this sense-making, not just hearing about how others have done it. We suggest a few strategies to consider as you begin to align your instruction with the vision for science education described in the *Framework* and the *NGSS.*

As you plan your modeling instruction, be sure to do the following:

- Focus on phenomena and data from those phenomena.
- Include the opportunity to develop a driving question based on the phenomenon that addresses a big and important idea and provides coherence in the unit.
- Engage students in repeated cycles of model evaluation and revision, and emphasize that models are based on empirical data and evidence.
- Ask students to use models to explain specific phenomena in the world around them.
- Engage students in the social nature of modeling—argumentation is involved in evaluation and consensus in building and applying models.

The modeling practice is powerful for students and teachers (Passmore, Stewart, and Cartier 2009; Schwarz et al. 2009). It is aligned with authentic scientific reasoning in many important ways, as we have described throughout this chapter. Look at what one teacher wrote as a testimonial to her use of modeling in the classroom:

> *Oftentimes, students only experience learning science as memorization of facts. It's quite frustrating as a teacher when we bring up a concept and immediately a student will say, "Oh, I already know that, or I already learned that." Upon further questioning they undoubtedly respond ... "it's just too hard to explain."*
>
> *Yes, because they don't really understand the things they've memorized.*
>
> *This is where models play a critical role in helping uncover what the kids "think they know" and how the revisions help them develop a conceptual understanding of the topic in which to apply to teaching (us) about the phenomena in general. I've seen this play out in my own classroom using models and although the process takes time, the students develop a strong sense of seeing themselves as scientists and understanding the world around them. The benefits to developing a consensus model encourages much more than just a scientific understanding. Students learn how to give and receive feedback, how to create and develop a "tool" to explain their understanding, and most importantly, students learned that they were scientists!*

As this teacher points out, engaging in the modeling practice allows students to be the sense-making agents in the classroom and creates a context for developing scientific understanding of the phenomena in the world. For teachers, models can provide windows into students' thinking, and models can also serve to make ideas and contributions from students in the class public—and potentially accessible as a tool for everyone in the classroom. The practice of Developing and Using Models can provide an anchor for engaging in the full range of science and engineering practices in the classroom and fulfilling the vision of a new kind of science education set forth in the *Framework* and the *NGSS.*

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