Chapter 36
Models in Science and in Learning Science:
Focusing Scientific Practice on Sense-making

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36.1 Introduction

Over the last few decades, there has been a “practice turn” in the philosophy of
science and, more recently, in science education. That is, there has emerged in both
fields an effort to understand and apply ideas about how science is actually practiced
to issues in philosophy and education.¹

What this practice turn has meant is that philosophers, along with other scholars
in science studies, have turned from seeking an account of science as a singular,
logical system for knowledge generation and evaluation and instead have begun to
focus more carefully on an examination of the nuances and context dependencies of
what scientists actually do to further their aims of making sense of the world. This
turn has been described as naturalistic or pragmatic, because it abandons some of
the assumptions and constraints of a more traditional philosophical approach in
favor of a more empirically based one and, in this way, offers more authentic
descriptions of the scientific endeavor.

Similarly, in science education, there has been much debate and discussion about
the distorted and decontextualized version of science that has come to be known as
“school science.”² There is an emerging consensus that the overarching emphasis on
a singular “scientific method” combined with a focus on memorization and test

from philosophy of science and Duschl (2008), Gilbert (2004), Matthews (1992), Osborne et al.
(2003), and Hodson (1992) from science education.
²See Duschl (2008), Hodson (1996, 2008), Rudolph (2005), and Windschitl et al. (2008b).

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preparation has contributed to a crisis in science education. Many able students are turning away from science, and more worrisome, there is an alarming lack of scientific literacy among the general public (e.g., Bauer 1992). The practice turn in science education, like the turn in the philosophy of science, has manifested itself in calls for science learning environments to become more authentic to science as actually practiced.

There are two primary reasons to situate science education reform in a consideration of scientific practice. The first is that by engaging students—in explicit ways—with a version of school science that is authentic, students may emerge with a more accurate view of the scientific enterprise. Having such a view will be useful to students as they consider new advances in science and in making decisions about their own futures. Second, because there is a great deal of alignment between how scientists think and reason and the powerful learning mechanisms that all humans use to navigate the world, engaging students in contexts that are authentic should produce a deeper understanding of and insight into the content of science. Indeed, there is good reason to believe that these two aims can be achieved with science education that has been carefully crafted to be authentic.\(^3\)

Meeting these goals requires developing learning environments that engage students in intellectual work that mirrors the work that scientists actually do. And, this means having a clear and coherent picture of the scientific enterprise, one that is developed by looking closely at how science is actually practiced with an eye to how that work can be productively translated and enacted in an educational context.

Thus, the practice turns in both science studies and in science education have parallel aims, to attend to the authentic nature of science as it is actually practiced, as well as a parallel challenge, to make sense of the messy intellectual endeavor so that some coherent understanding of the scientific enterprise can be described. Scholars in science studies have examined the complexity of scientific practice from a range of perspectives. Authors have focused on the social structure of science, the cultural and epistemological norms, the day-to-day practices and routines of scientists, the role of tools and material forms, and the reasoning and problem-solving strategies used in scientific practice. Given the nuances and complexities of scientific practice, it can be difficult to conceive of how it can inform the design of science learning environments without leaving us with an account of science that is so diffuse and unstructured to be of practical use.

One way to address the complexity problem is to emphasize the cognitive endeavor of science by focusing on the practice of science and how it supports making sense of how the world works. Such a view does not ignore other perspectives; as Giere and Nersessian have argued, scientific cognition is necessarily embedded in sociocultural contexts where it is shaped and supported by complex interactions with other humans and with material forms. However, a focus on cognition can provide one clear avenue for translating scientific practice into science classrooms.

\(^3\)See, for example, Stewart et al. (2005), Duschl (2008), Engle and Conant (2002), Ford (2008), Duschl and Grandy (2008), Lehrer and Schauble (2004), and Roth and Roychoudhury (1993).
This account makes supporting sensemaking primary and asks how can the social, cultural, and material aspects of science classrooms be structured so that scientific reasoning is supported. It is from this starting point—that a central aim of science education is to engage students in scientific sense-making—that we move forward with for this chapter.

Increasingly, scholars in the history and philosophy of science have turned to examining the pivotal role that models and modeling play in organizing the cognitive activities of practicing scientists. A recognition of the importance of models and modeling in science education has been on the rise as well. There are important connections to be made between the science studies efforts and those in science education around the centrality of models and modeling in the practice of science. A careful consideration of the nature and use of models in science can provide one way to organize our understanding of scientific practice and frame the way we translate this practice into science classrooms to support meaningful sense-making.

36.1.1 Driving Question and Overview

In this chapter we will examine how historians, philosophers, and psychologists have viewed the role of models in science. In particular we are interested in how models function as reasoning tools that allow one to bound, explore, organize, and investigate phenomena and to develop explanations, generalizations, abstractions, and causal claims about those phenomena. We hope to draw out the nature and function of models as context-dependent tools that productively organize a range of sense-making work that scientists undertake in their practice. Sections 36.1 and 36.2 of this chapter are intended to answer a particular driving question:

*How do models function to structure and organize scientific practice around sense-making?*

To address this question, we first present a rationale for focusing on models; then address ontological and epistemological questions about the nature, form, and development of models; and finally examine how models are actually used in scientific practice.

Ultimately, our goal with this chapter is to unify the views from the science studies literature on how models operate in scientific work and to explore the implications of this view for science education. In order for learning environments to reflect authentic science, they need to be designed to mirror the cognitive activities of scientists. In Sect. 36.3, we address the question:

*How can a model-based view of scientific practice be leveraged to organize and focus classroom activity in support of sense-making?*

To address this question, we propose a framework for organizing ideas about model functions in science education and apply that framework to a collection of studies in the science education literature. The chapter ends with a consideration of a number of practical and theoretical implications and recommendations.
36.1.2 **Rationale for Model Focus: “Why Models?”**

To begin, we briefly examine work in history and philosophy of science that motivates our examination of models in science and science education. Much of this scholarship draws on Giere’s seminal work in this area, *Explaining Science*. In it he made a deliberate turn away from the “general program” in philosophy of science to a more naturalistic one that examined how scientists actually go about their work on a cognitive level. He began with the assumption that “the representations that scientists construct cannot be radically different in nature from those employed by humans in general” (Giere 1988, p. 62); that is, the sense-making apparatus common to all humans is at work in science as well. The layperson’s mental model is not different in kind from the widely accepted scientific model; rather, scientific models are more carefully constructed and systematically evaluated extensions of a more basic cognitive strategy.

This turn toward understanding the meaning making that scientists, as humans, do, rather than characterizing the products of their work on a structural level, emerged from what became “the cognitive study of science,” in which mental models play a central role. There was a historically parallel, but independent, move in the philosophy of science from a “syntactic” to a “semantic” view of scientific theories. The latter moves beyond the abstract structure of theories to include issues of the meaning of scientific terms and the truth of scientific statements. In the semantic view of theories, models, still understood as logical rather than mental constructs, are central. Melding these two traditions has been a complicated process (see Downes 1992; Knuuttila 2005). Neither tracking these historical developments nor analyzing their various commitments is our intent here as this has been skillfully done in a number of recent papers for the science education audience. For our purposes, the significance of these developments is that they gave prominence to the idea that models play a central role in scientific sense-making. Fully unpacking why a focus on models in science is useful and how models operate in scientific sense-making requires moving beyond purely philosophical concerns and bringing together a more integrated science studies approach that combines cognitive-historical, psychological, and ethnographic methods.

For example, over the past 15 years, Nancy Nersessian and her colleagues have undertaken a psychological approach to studies of actual scientific practice using both cognitive-historical and contemporary ethnographic techniques. They have spent years observing, documenting, and talking to scientists as they do their day-to-day work (e.g., Osbeck et al. 2010). From these studies has emerged a clear sense that models are at the center of the day-to-day work of science; they are the functional units of scientific thought. As Nersessian explains, mental modeling is the underlying cognitive machinery that makes model-based reasoning so fundamental.

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4See Adúriz-Bravo (2012), Bottcher (2010), (Develaki 2007), and Koponen (2007 and this volume). Please also see a special issue of *Science & Education* (Matthews 2007) for a careful treatment of models and modeling for the education audience.
to human sense-making. It is the general machinery that underlies our ability to engage in the more formalized scientific strategies of generating representations, using analogies and thought experimentation.

Building on the foundational works of Giere and Nersessian, there has been a proliferation of scholarship in science studies related to uncovering the role of models in science. For example, Morgan and Morrison (1999), in their edited volume, *Models as Mediators*, pulled together a range of articles that explored the ways in which models function in a variety of disciplinary contexts. And, numerous other scholars situated in biology, chemistry, physics, and economics have undertaken both historical and contemporary descriptions of model use in science. Similarly, in the science education community, there is an emerging movement that acknowledges models and modeling as important aspects of scientific practice (e.g., NRC 2011; Windschitl et al. 2008b). Taken together, these studies provide a rationale for organizing science instruction around models and the primary motivation for this chapter: Models are central to scientific sense-making. They provide a way to organize our understanding of scientific practices and a way to understand the purpose of scientific activity.

Alternative organizing frameworks that centralize other aspects of scientific practice are certainly possible. To focus on models is a choice that, as we explore in this chapter, has particular affordances. Specifically, an explicit focus on modeling helps organize scientific practices such as representation, experimentation, and argumentation around the purpose of making sense of phenomena rather than as discrete activities. Although, this unification is seamless in actual scientific practice, in science education, unification can be more challenging. In the next section we draw on science studies to support the claim that models are central to the sense-making practices of scientists and examine the implications for science education.

## 36.2 Models in Scientific Practice and Science Learning

This section builds toward an understanding of models as context-dependent tools for making sense of phenomena by drawing on the work of philosophers and historians who emphasize the functional role of models in science. First, we address ontological questions about the nature and form of models, we then address epistemological concerns related to model construction and evaluation, and finally, we turn to a functional account of how models are used in scientific practice. What emerges from this account is a definition of models that emphasizes their utility as tools for sense-making as well as a description of the specific ways in which models

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5 In biology, see Cooper (2003), Lloyd (1997), and Odenbaugh (2005, 2009); in chemistry see Suckling et al. (1980); in physics see Cartwright (1997, 1999), Hughes (1999), and Nersessian (1999, 2002); in economics see Boumans (1999) and Morrison (1999). See also Auyang (1998) for comparison across biology, physics, and economics.
serve this function in science. This view of models, embedded in scientific practice, can provide a productive framework for organizing science education environments which is the focus of Sect. 36.3.

36.2.1 What Are Models? Ontological Concerns

Few terms are used in popular and scientific discourse more promiscuously than “model.” (Nelson Goodman 1976, p. 171, as cited in Odenbaugh 2009)

It can be challenging to define models in a concise way. Nevertheless, drawing on pragmatist philosophers, we identify several key attributes of scientific models:

1. Models are defined by the context of their use.
2. Models are partial renderings of phenomena.
3. Models are distinct from the representational forms they take.

In this section we discuss each of these features and discuss the implications of this definition of scientific models for education.

36.2.1.1 Models Are Defined by the Context of Their Use

Nersessian (2002) refers to the cognitive processes involved in deciding how to construct a model as mental modeling. Note that she makes a distinction between mental models, often described as knowledge structures stored in the long-term memory, and mental modeling as a process of human sense-making. We take up the latter view of model-based cognition as a flexible, context-dependent process whereby humans interpret and reason about situations by selecting and drawing together cognitive resources. Conceived of in this way, models are dynamic entities that are constructed and used as needed.

Although the word model is used to describe a wide range of entities in the sciences, one cannot actually provide a clear definition of what is and is not a model in an abstract sense. As Teller states:

The point is that when people demand a general account of models, an account which will tell us when something is a model, their demand can be heard as a demand for those intrinsic features of an object which make it a model. But there are no such features. WE make something into a model by determining to use it to represent. (Teller 2001, p. 397, emphasis in original)

For these reasons we fall back on a very basic framework for a model, that models are sets of ideas about how some aspect of the world works. Models are entities that represent some aspects of a phenomenon to some degree. But which of those aspects and to what degree will not be uniform across contexts. Thus, while some philosophers have attempted to specify this relationship as an isomorphism between some source (the world) and some target (the model), we use the more relaxed
criterion of similarity (Giere 1988) to describe the relationship between models and phenomena. A slightly more precise version of the similarity criterion is proposed by Teller who describes similarity in terms of properties: Systems have properties, and some of these (depending on the objective of the modeler) will be part of the model (2001, p. 399).

Perhaps more important than defining what a model is defining what it is not. Appealing to similarity does not imply that any object that is similar to a natural phenomenon is a model. A globe, for example, is not a model of the Earth by default. It becomes a model when it is used to make sense of some puzzling pattern or answer some question. The same object can both be a model and not be a model depending on how it is being used.

Pragmatist philosophers, beginning with Giere (1988), have argued that the relationship between models and the world only makes sense in the context of their intended use by some cognitive agent. In defining models we cannot simply consider how the model relates to the phenomenon it represents; we must explicitly consider the role played by the cognitive agent (see Fig. 36.1, Giere 2004; Knuuttila 2005). By explicitly drawing attention to the cognitive agent in the system, we end up with a definition of models that foregrounds their function in reasoning. It is the cognitive agent, the modeler, who will decide how to bound, filter, simplify, and represent the phenomenon to generate a model. Which features need be shared and to what degree will depend on the way in which the model user wants to understand that phenomenon.

36.2.1.2 Models Are Partial Renderings of Phenomena

Understanding models in terms of their use can also help clarify the relationship between models and real-world phenomena. It is common to see models referred
to as abstractions, simplifications, idealizations, or simply representations of phenomena. Specifying the exact nature of the relationship between models and the world has been a central point of debate in the philosophy of science literature (Downes 1992; Knuttila 2005). As Downes describes, the motivation for this debate has been to say something philosophically robust about models as knowledge structures—to answer the question what can models really tell us about the world? Many proponents of the semantic view have attempted to define the relationship between models and the world as isomorphic. However, for Downes and other pragmatists, the attempt to define a singular relationship between models and real-world phenomena misses the mark. Neither an account of models that focuses exclusively on isomorphism nor an account of models as purely analogical nor any other general account will apply in a universal sense to the variety of different kinds of scientific models that have been historically and continue to be used by practicing scientists (Downes 1992).

Cartwright (1999) similarly challenges the notion that phenomena can be mapped to general theories. Instead, she acknowledges that different phenomena may require models, which vary in the degree to which they make different simplifying assumptions. Cartwright’s account is a rejection of the universalism of laws and an acknowledgement of the diversity of phenomena themselves, each of which require its own model formulation. Cartwright describes how a coin dropped from a height can perhaps reasonably be modeled using a simple Newtonian model. But the same model cannot help account for the motion of a dollar bill. The result is that reality is covered by a “patchwork” of models (see Fig. 36.2). This metaphor begins to complicate the possibility that there is a single way to characterize the relationship between models and the world.

Rather than attempt to map a one-to-one relationship between models and phenomena, Morrison and Morgan (1999) describe models as “partial renderings” that can differ widely in the extent to which they accurately represent real systems. They describe how a model of a pendulum can be simple and abstract when used as a means of making sense of simple harmonic motion but can be refined with a series of corrections that increase the complexity of the model as well as its success in making accurate predictions. There is no singular model of a pendulum; rather there are a group of overlapping models of a pendulum, each of which can be used to reason about a pendulum in a different way.

When the importance of a cognitive agent is recognized, a better metaphor for the relationship between models and phenomena is a geometric one proposed by Auyang (1998). As Auyang describes, attempts to define a one-to-one correspondence between the world and our theoretical understanding of it necessitate a finite geometry in which our understanding maps onto the world like “a single global coordinate system covers an entire manifold” (1998, p. 74). As an alternative, Auyang proposes we think of science in terms of a differential geometry, in which the manifold is covered by overlapping local coordinate systems (see Fig. 36.2). Thus, Cartwright’s patchwork is best understood not as a regular quilt with patches stitched together to create a complete understanding. Instead, the patchwork is much more irregular, with patches of different sizes and shapes overlapping with
one another, creating areas with many layers of coverage and possibly other areas with large gaps. It is the model user who decides which patch to apply to the world, depending on her aim.\footnote{There are two recent books that develop the “patchwork” idea in quite rich directions for those readers who might want an even more sophisticated version of these ideas: Mark Wilson, \textit{Wandering Significance}, Oxford Univ Press, 2006, and William Wimsatt, \textit{Re-engineering philosophy for limited beings}, Harvard Univ Press, 2007.}

\section*{36.2.2 Models Are Distinct from the Representational Forms They Take}

Just as there are potentially multiple models that can be used to make sense of a phenomenon, there are also multiple representational modes that any given model can take. Knuuttila (2005) describes modeling as involving two levels of representation. The first level involves choosing the attributes of the system that are relevant to include in a model. Such choices are dependent on the aim of the modeler as noted above. The second level involves making a choice about \textit{how} to represent the relevant attributes of the system in some material form. Often these two levels cannot be separated—choices about what features are important will suggest a particular form just as the choice of a material form will afford or constrain what is attended to. Nevertheless it is worth pointing out that essentially the same ideas can be conveyed in a variety of representational modes including diagrams, equations, physical models, or written text. These different forms should not be conceived as different models per se; rather one should focus on the differences in representational mode.
Too great a focus on the material form of a model can be problematic because it tends to collapse the triadic relationship (between model, cognitive agent, and phenomenon) back into a dyadic one (model and phenomenon only) (see Fig. 36.1). A diagram of the cell is referred to as a “model of the cell,” but this diagram by itself is merely a depiction of a physical object because it does not suggest what such a diagram is good for. Thus, despite the widespread usage in education circles of the word model as applied exclusively to physical objects (like Watson and Crick’s tin and cardboard DNA molecule), it is not the material aspect or embodiment of the object that makes it into a model.

In the DNA example, the physical object was deployed to figure out something in the world; it was the physical manifestation of the key features of DNA that were relevant to understanding the mechanisms of inheritance. The material aspect of Watson and Crick’s model was absolutely critical, but it was not the materiality that made it a model; rather it was how the abstract ideas about the structure and function of DNA along with Franklin’s x-ray data were embodied in the material object and how it could then become a tool for reasoning about how the molecule functioned. The physical mode of representation was important because it allowed Watson and Crick to visualize precisely how the bond angles among atoms fit together and allowed them to feel confident that their structural understanding was correct. But, as the final line of their manuscript makes clear, that understanding was crucial for making sense of how DNA could possibly function in transmitting genetic information (Watson and Crick 1953).

To return to the of/for distinction made earlier, the three-dimensional structure of DNA is best understood not simply as a model of DNA but as a model that included the relevant structural elements of the molecule, thus allowing them to use it for developing a deeper understanding of its function. Educators tend to refer to the representational forms themselves as models (i.e., this is a 3-D model of DNA) rather than referring to representational systems as a whole (i.e., this is a physical representation of a DNA molecule that allows one to reason about how this molecule’s structure relates to its function in biological inheritance). Unfortunately, this shorthand can promote confusion by foregrounding the form and backgrounding the intention. Being unclear about this issue can lead teachers to conclude that they are doing the scientific practice of modeling in their classrooms whenever they have their students working with physical objects. In fact, it is the cognitive activity—the sense-making—that should provide the primary criterion for determining if students are engaged in modeling. This kind of sense-making goes well beyond merely labeling parts and memorizing functions.

36.2.2.1 What Is a Model? Implications for Science Education

We can use this expanded understanding of models to gain some additional traction in defining models in science education: Models are not simply of phenomena, they are tools to be used for some reasoning about that phenomenon (Fig. 36.1). This distinction has important implications for decisions about what kinds of models to include in science curricula and for how we assess students’ abilities as modelers.
A number of recent articles in the science education literature attempt to provide a typology of models in science toward a goal of finding a list that is inclusive and useful to educators for making decisions about what kinds of models to bring into science classrooms. These typologies emphasize the importance of carefully considering the context when making decisions about the model form and content in instructional settings. However, one challenge of these lists is that they can be difficult to interpret on a philosophical level and use in science education because they do not distinguish models from their representational forms. For example, Harrison and Treagust (2000) present a typology that orders models from concrete scale models, through abstract theoretical models, to complex dynamic systems simulations. This ordering is meant to reflect conceptual demand; concrete scale models (e.g., a scale boat) are less challenging than process models (e.g., a chemical equation) and are therefore positioned lower in the typology (p. 219). Harrison and Treagust suggest a learning progression that first introduces students to concrete models and moves toward introducing more abstract models.

The general point that the models used in educational contexts must be chosen in accordance with the abilities of students is an important one but is made more clear when models and their representational forms are kept distinct. A scale model of a boat can be a less sophisticated reasoning tool than a chemical equation, but this has less to do with the representational form than it has to do with the ways in which the models are used. If the scale model of the boat is used to merely represent surface features of a boat, this is not very sophisticated, and indeed the cognitive demand may be relatively low. However, if the scale model of the boat is used to highlight how boat shape relates to buoyancy, then more intellectual challenge is introduced. A scalar representation of a boat is not a scientific model at all, whereas a scalar representation of a boat that can be used for reasoning about the phenomenon of floating by illustrating scientific ideas about displacement could be one way of representing a model for buoyancy. Thus, the cognitive demand of a particular model has less to do with the form it takes and more to do with the function it serves.

By defining models in the context of their use, the focus shifts to choosing a model that can be used to make sense of the target phenomenon in a way that is appropriate for the cognitive agent. This might mean that in some classroom contexts, a smaller set of constructs are introduced and simpler relationships are highlighted than are present in the model versions used in the scientific community. This point is made by Gilbert and colleagues in their discussion of curricular versus scientific models. Curricular models are simplified versions of scientific models that are specifically adapted for classroom use. Gilbert (2004) suggests that teachers must choose these curricular versions with an understanding of “the scope and limitations of each of these models: the purposes to which they can be put and the quality of the explanations to which they can give rise” (p. 126). That is, teachers and curriculum designers need to carefully select or construct versions of scientific models with which students can productively think.

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7See, for example, Boulter and Buckley (2000), Coll and Lajium (2011), Gilbert (2004), and Harrison and Treagust (2000).
Introducing a model into a classroom also includes, as Harrison and Treagust (2000) suggest, the need to consider the representational form. However, because of the dual nature of the representational role of models, two sets of questions about what kinds of models to introduce to students must be asked: First, with what set of ideas do we want students to engage, and second, what representational mode or modes can support interaction with those ideas?

It is important to separate the notion of the model from the particular representational form it takes. One reason for this has been to keep students focused on the success of the model as a reasoning tool as opposed to particular features of the representational form that can sometimes distract them from the salient conceptual elements of the model. For example, when first graders were asked to design a physical object that “works like an elbow,” they tended to focus on the surface features of the representation, adding details to the models that had only to do with physical resemblance between their replicas and real elbows (Penner et al. 1997). Part of the reason they did so seems to be because the task was purely a representational task—make the elbow—and students responded by making physical replicas of elbows.

Imagine if the task had been rephrased so that it foregrounded a sense-making aim and backgrounded the representation, e.g., how is it that an elbow allows you to pick up something? This could have been done by introducing some flexibility in the choice of representational form instead of requiring students to build a physical model or by reframing the task around explanation as opposed to design. In such a scenario, the task would have been framed such that the purpose—to understand something about how elbows work—would have been highlighted. A follow-up study by Penner and colleagues demonstrates a shift in this direction where the students began to explore ideas about the elbow as a fulcrum, introducing ideas about torque and distance. In this second study, the model was no longer seen as one of the elbow, it was for understanding how lever systems like the elbow actually work (Penner et al. 1998).

The reason the off for distinction is so powerful for education is that, again, it situates the model in the context of its use. It highlights function over form. In addition, it helps to keep the focus on reasoning and making sense with the model rather than reducing models to just another thing to be learned by rote in the science classroom. Models should be deployed in science classrooms as dynamic entities that help organize and focus a class of cognitive activities toward a clear sense-making goal.

The second major implication of defining models in terms of their intended use is that there is no single model of any particular object or system but rather many possible models, each of which has different affordances and constraints for reasoning about that phenomenon. In the science education literature, mental models are sometimes used to refer to static representations of students’ ideas stored in long-term memory. Students are often described as having models “of” particular phenomena. For example, Gilbert (2004) states that “[a]ll students of chemistry must have a mental model, of some kind, of an ‘atom,’ all those of biology of a ‘virus,’ all those of physics of a ‘current of electricity’” (p. 117). Often students are asked to
externalize their internal mental models as drawings (e.g., Coll and Treagust 2003; Gobert 2005). We have seen this work interpreted to mean that students have a singular view of a particular entity or process with the implication that if this view is incorrect, it must be replaced with the correct consensus model.

Defining models in terms of their purpose allows for the possibility that students, like scientists, have multiple sets of ideas about scientific phenomena. The ideas students have about an atom are likely to vary depending on how they are being asked to think about atoms. For this reason it is important when asking students to generate models to be clear about the purpose of the activity. Asking students to depict a generic model (e.g., “Draw me your model of an atom.”) is an underspecified task because it does not help them, as cognitive agents, make informed decisions about which features and relationships are important to represent. Consider the difference in the salient ideas that the student would need to draw on if she was trying to reason about bonding versus nuclear radiation.

If instead models are defined as sets of ideas that are activated in the working memory in response to a particular aim, we shift the focus from whether or not students possess a correct mental model to helping draw out the productive ideas that students have for making sense of particular phenomena. This can help orient educators to drawing out and building on students’ ideas rather than attempting to replace misconceptions (c.f. Hammer 1996). Modeling in the science classroom has the potential to draw upon the powerful learning and reasoning resources that all students bring to the classroom and to create an environment in which the students are active learners. This approach could result in students who develop their capacity to reason about the complex and interesting world and could go a long way toward addressing the rote approach seen in so many contemporary classrooms.

### 36.2.3 What Makes a Good Model? Epistemological Concerns

Given that models are defined only in the context of their use, it follows that there is no context-independent way to evaluate a model. Models are built with an understanding of the epistemological criteria that are relevant to the question at hand, and they are evaluated with an understanding of their intended use. This leads us to consider two epistemological concerns:

1. A focus on models means merging the contexts of discovery and justification.

#### 36.2.3.1 Merging the Contexts of Discovery and Justification

Practice-based philosophers acknowledge that there is no meaningful distinction in practice between the model development and evaluation. In his 1999 chapter in *Models as Mediators*, Marcel Boumans explores the relationship between model building and model justification. He argues that “models integrate a broader range
of ingredients” that include theory and empirical data but also metaphors, analogies, mathematical concepts, and techniques. The central claim of his chapter is that this integration is satisfactory when the resulting model can be (1) used as a solution to a theoretical problem, (2) an explanation of an empirical phenomenon, (3) an indication of some possibilities, and (4) a way to mathematically conceptualize a problem. This is an account of modeling that is situated in the context of function, aims, and cognitive payoffs.

Boumans’ central thesis is that despite the way in which stories about model development get told, in practice, the “context of discovery” and the “context of justification” are completely intertwined. It is by simultaneously attending to both the theoretical/empirical world and the more pragmatic aims of the modeler that progress on model development is made and justified. The steps are not distinct. One does not build something and then check to see if it does what it is meant to do. Rather one builds something with ongoing and critical attention to the purposes it is supposed to serve. In this way, Boumans explains that “justification is built-in.”

Similarly, Nersessian (1992, 2002), by focusing on the cognitive activities of scientists, combines the contexts of discovery and justification into the context of “development” where ideas are articulated and evaluated in a process that is fundamentally creative. New ideas arise in this context not completely de novo but in conversation with existing ideas. She describes how, for example, Maxwell’s revolutionary ideas about electromagnetism were borne out of analogies with existing models in mechanics. Further, in the context of development, emerging ideas are not simply held up against a set of rigid standards of justification, but they can interact with those standards to change the rules of the game. Einstein’s new framework of relativity fundamentally shifted the criteria against which models would be judged.

### 36.2.3.2 Models Must Balance Trade-Offs in Epistemological Criteria

Both the Boumans and Nersessian accounts point to the contingent and contextual nature of scientific reasoning and suggest that models will be subject to different epistemological criteria depending on how one intends to use them. They also suggest, as ecologist Richard Levins argued, that “[t]here is no single, best all-purpose model” (1966, p. 7). Levins argued that for both cognitive and methodological reasons, modelers must often choose among the desirable, but often conflicting, epistemic aims of realism, precision, and generality. For example, a fisheries biologist interested in population projections of a species of interest might choose to sacrifice generality in order to construct a model that can generate accurate predictions of population fluctuations, while an ecologist, like Levins himself, might forgo predictive precision in the interest of general explanatory power. The main point to take away from Levins’ argument is that modelers will and should build different models depending on their particular aims. The implication is that there is not a single type of model or modeling that can address all biological problems equally well; depending on the question at hand, a biologist will want to choose the model that is the best tool for the particular job.
36.2.3.3 Implication: The Need to Contextualize Meta-modeling Knowledge

When engaging students in the context of model development (i.e., model construction and evaluation) it is important to make them aware of criteria used to judge models but also to help them develop the expertise to recognize which of these criteria are relevant for their purposes at a specific point. A recent study by Pluta et al. (2011) highlights the importance of helping students develop ideas about what makes models “good” in ways that make the context explicit. Without significant instruction, middle school students were able to generate a variety of epistemic criteria for evaluating scientific models. When prompted to list the features of a “good” model, students responded with criteria such as communication, explanatory power, and fit to data. However, the most common responses had to do with the amount of detailed information presented in the models, suggesting that students were thinking of models primarily as useful for conveying information, much as a textbook diagram would.

Looking closer at the nature of the task in this study, students were asked to evaluate a variety of static representations of models including diagrams, pictures, and text similar to what they might see in textbooks (Pluta et al. 2011, p. 500). The task was framed without reference to a particular problem, question, or aim. Given that in the context of this task students were interacting with static, final form models, it is not surprising that many students described models as tools that help communicate ideas, rather than objects to support scientific inquiry. Nevertheless, this study suggests that students do have some resources for thinking about using models in a variety of ways and it supports the argument that a goal of instruction should be to reinforce and refine these ideas with reference to particular scientific aims. We caution against teaching epistemic criteria to students as a normative list of characteristics of “good models” in an abstract and universal sense but instead advocate for instruction that helps students develop and attend to such criteria in the course of developing and using models in context.

36.2.4 How Are Models Used? Functional Concerns

The primary utility of the practice turn is that it has begun to specify, in more detail, the ways in which models function in scientific practice. Once one takes up the “models for” orientation, then a crucial next step is to consider what the cognitive agent is doing in more detail. In what follows we build on what has so far been a general argument that models are context-dependent tools for reasoning and now turn to a more specific account of the ways in which these tools can support sense-making in science.

Here the focus is on three scholars from the science studies literature who have taken up the challenge of elaborating a functional analysis of models in science. Jay Odenbaugh (2005) presents an argument from contemporary philosophy of biology for the legitimacy of modeling in biological practice and the range of uses they are
Nancy Nersessian approaches the problem from the perspective of cognitive science, using cognitive-historical case studies of physicists and contemporary ethnographic methods to unpack the affordances of model-based reasoning. Stella Vosniadou (2001) considers how models function in scientific sense-making by examining similarities between the reasoning of young children/lay adults and scientists.

36.2.4.1 Odenbaugh: Cognitive Benefits of Modeling in Biology

Philosopher of biology Jay Odenbaugh (2005) presents an argument emphasizing the functional utility of modeling in ecology. He states, “model building is first and foremost a strategy for coping with an extraordinarily complex world” (p. 232). He unpacks the strategies of modeling in ecology and the associated cognitive benefits of engaging in these strategies. While, his analysis draws on work in biology, we find it useful for exploring the role of models in science more generally.\(^8\)

Drawing on the work of Levins (1966), Odenbaugh explores five major pragmatic uses for models in biology and their associated benefits: (1) simple, unrealistic models help scientists explore complex systems, (2) models can be used to explore unknown possibilities (3) models can lead to the development of conceptual frameworks, (4) models can make accurate predictions, and (5) models can generate causal explanations. The focus of his argument is that the first three roles of models have been underemphasized in comparison to the latter two.

In his exploration of the first point, Odenbaugh describes how simplification is a purposeful strategy that scientists use in a number of different ways. For example, Odenbaugh describes how simplistic optimality models, which assume that natural selection is the only mechanism shaping natural systems, are used as a baseline from which to consider and explore deviations. That is, simple models can help scientists by allowing them to begin to unpack the reasons why a false model is wrong (see also Wimsatt 1987).

A simple model can be compared to successively more complex models as a systematic strategy for locating error. Odenbaugh illustrates this point with an account of how understanding the deficiencies in the simplest version of the Lotka-Volterra predator–prey model, which is empirically unrealistic, has led to a productive elaboration of increasingly detailed models. Importantly, these models not only make more sense empirically, they also include assumptions that are much more plausible given what is known about natural populations.

In posing a second role for models, Odenbaugh examines how models afford opportunities for exploring possibilities. Rather than representing what is, models can help scientists think about what might be. For example, Odenbaugh describes how ecologist Robert May explored the possible patterns that would emerge from a simple logistic model of population growth. His analysis revealed that increasing

\(^8\)See Svoboda and Passmore (2011) for a much more thorough treatment of Odenbaugh’s framework.
the per capita rate of increase (R) could yield chaotic dynamics. The significance of this finding was that it oriented ecologists to the possibility that even relatively simple ecological systems could exhibit complex chaotic patterns for certain parameter values.

The third role for models is in leading to the development of new concepts. Odenbaugh (2005) describes how biologist Robert May chose to represent the overall number and degree of interactions in an ecological community in terms of a “connectance” parameter C, which he defined as the proportion of all pairwise species interactions that were not equal to zero. May’s analysis suggested that C played a key role in the stability of the community over time. While May’s model was later criticized, Odenbaugh describes how his attempt to operationalize and interpret the role of C opened up a discussion in the ecological community surrounding the appropriate ways to conceptualize community complexity and stability. This analysis marked the beginning of a proliferation of ideas in the ecological community as well as a marked increase in experimental work in community ecology that extended well beyond the original model.

In sum, the essence of Odenbaugh’s argument is that matching reality is not the only role for models in biology. Making predictions and explanations are important roles for models, but there are others as well that do just as much to support sense-making. Odenbaugh wants to ensure that the utility of the exploratory role of models in generating new ideas and new ways of thinking is recognized as well.

36.2.4.2 Nersessian: Model-Based Reasoning in Physics

Nancy Nersessian and her colleagues have investigated the role of models in science both through cognitive-historical case study analyses (e.g., 1992, 1999, 2002) and more recently in laboratory settings (Osbeck et al. 2010). One of her primary aims has been to explore how models help scientists reason about phenomena by attending to the cognitive processes of scientists and how these processes are situated in scientific practice. In her work Nersessian has identified three types of modeling practices that commonly co-occur in case studies of scientific problem solving: (a) visual reasoning, (b) analogical reasoning, and (c) thought experimentation (simulative reasoning).

In a case analysis of the development of electric-field theory, Nersessian describes the strategies used by Faraday and Maxwell (for a detailed account see Nersessian 1992). Faraday and Maxwell were motivated by a desire to make sense out of a puzzling phenomenon: apparent attractions between objects at a distance. This phenomenon is easily observable by, for example, rubbing a balloon against some fabric and noting that it can now “stick” to the wall. Both scientists made extensive use of diagrams to organize and visualize their emerging understanding of how electric phenomena might work. These representations served to highlight the important structures and relationships between them and served as external objects that could be actively reasoned with. As Nersessian (2002) explains, visual representations do more than hold the ideas in a model—they help focus the reasoner on
salient features. They also support simulative reasoning by helping create a visual image that can be animated in the mind. Finally, visual representations provide a way to share ideas with the community. Preparing for this sharing event can force the modeler to make ideas clear and the act of sharing such representations is a productive means of extending the reasoning process out to the larger scientific community. It is the interaction between these externalizations and the underlying model ideas that can lead to breakthroughs for the reasoner.

Analogical reasoning is a form of reasoning that is common in many of these analyses. In forming his understanding of the concept of electricity, Maxwell leveraged analogies from classical Newtonian mechanics. He reasoned that electricity could be analogous to other continuous-action phenomena such as heat, fluid flow, and elasticity (see 1992). For example, using a fluid flow model to map out a similar model of electricity was a crucial part of early work in developing understanding of electric forces.

It is also evident from Nersessian’s analysis of his writings that Maxwell relied on simulative thought experimentation to reason through the consequences of his model. This strategy of imagining how a phenomenon might change if certain conditions are changed was also famously used by Galileo. As Nersessian describes:

According to Aristotelian theory, heavier bodies fall faster than lighter ones. This belief rests on a purely qualitative analysis of the concepts of ‘heaviness’ and ‘lightness’. Galileo argued against this belief and constructed a new, quantifiable representation through sustained analysis using several thought experiments and limiting case analyses…..He calls on us to imagine we drop a heavy body and a light one, made of the same material, at the same time. We could customarily say that the heavy body falls faster and the light body more slowly. Now suppose we tie the two bodies together with a very thin—almost immaterial—string. The combined body should both fall faster and more slowly. It should fall faster because a combined body should be heavier than two separate bodies and should fall more slowly because the slower body should retard the motion of the faster one. Clearly something has gone amiss in our understanding of ‘heavier’ and ‘lighter.’ (Nersessian 1992, p. 28)

Galileo used this strategy to explore the meaning of the concepts of heavy and light and ultimately reveal the flaws in the Aristotelian model.

Nersessian’s focus on model-based reasoning in science draws out some specific cognitive strategies that scientists have at their disposal for making sense of the world. Her analyses make clear that models and the suite of cognitive strategies that they support have helped scientists organize and extend their ideas in ways that have been extremely productive. Further, her account suggests that these same strategies can be productive for students of science (Nersessian 1989, 1995).

36.2.4.3 Vosniadou: Models and Learning Science

Stella Vosniadou has explicitly applied ideas about the cognitive utility of models to science learners. In her 2001 paper, she explores the analogous ways that children and scientists reason with models. Like others, she puts the mental models of children and lay adults on the same dimension as the models of practicing scientists. In her analysis she explores the functions that models play in children’s reasoning.
She summarizes her findings with three related functions of models in reasoning: “(a) as aids in the construction of explanations, (b) as mediators in the interpretation and acquisition of new information, and (c) as tools to allow experimentation and theory revision” (p. 359).

In the first sense, Vosniadou notes that models serve a generative function in that they allow the cognitive agent to reason about situations or phenomena that are beyond his or her experience. In her studies of children and lay adults and their views of the shape of the earth, she found that the model served as the “vehicle through which implicit physical knowledge enters the conceptual system” (p. 361). Once this knowledge was articulated in the form of a model, most of her subjects answered questions using a consistent form of this model for the remainder of the study session and were observed to use the abstract ideas to answer specific questions about the earth and objects on it.

Just as the cognitive agent uses the model to generate explanations, so, too, does the model provide a strong filter through which new experiences or information is interpreted. In a study of children’s ideas about the day/night cycle, Vosniadou found that the models children had clearly influenced how they interpreted the questions asked of them, just as scientists’ models influence how new data are interpreted.

And finally, Vosniadou explores how existing models serve to inform and constrain new ideas and models. In her studies she found that children used their existing ideas to formulate new ones so that a clear connection could be drawn from initial ideas to how those ideas changed over time in the face of new information.

The importance of Vosniadou’s contribution is to point out that reasoning with models “is a basic characteristic of the human cognitive system and the use of models by children is the foundation of the more elaborate and intentional use of models by scientists” (p. 367). The fundamental role of models in interpreting and generating new knowledge is central to science and from this premise more specific accounts of the function of models (as delineated above) are possible. Vosniadou’s connections between the cognitive work of scientists and children imply that using a modeling framework in education is not only viable but desirable.

From these three scholars, there are a number of ways of describing how models function in science and how this functionality might extend into learning environments. In this final section, we synthesize across these ideas to propose a framework that demonstrates how models, modeling, and model-based reasoning can serve to organize classroom science and focus students’ scientific reasoning on making sense of the natural world.

### 36.3 A Framework for Models in Science Learning

What follows from Sect. 36.2 is that what makes something a model and how a model is developed over time is inextricably linked to the ends it is put to. That is, at a fundamental level, the focus should not be on a model of something as an end in itself; rather models are for particular sense-making aims. Making sense of a
phenomenon does not typically happen all at once. Rather, one makes sense of a phenomenon by taking the problem in pieces. As these individual pieces come together to inform and constrain the model, both the model and the knowledge products that result from model use become more productive toward the ultimate aim of understanding how something in the world works. Thus, broadly conceived, we delineate two major classes of model-based reasoning. In Fig. 36.3, we have depicted the act of reasoning with the model to produce knowledge products and the act of reasoning about the model—developing and refining it—using these knowledge products, always toward the ultimate end of sense-making. Thus, the model is a means to an end, not an end in itself.

If models (whether explicit or not) serve as the basis for most, if not all, sense-making endeavors, then getting specific about the myriad ways that model-based reasoning plays out can productively inform science educators as they endeavor to craft more authentic learning experiences for students. Figure 36.3 above is one way to parse reasoning and the products of that reasoning. Of central importance in this figure is the idea that it is through iterating between reasoning with the model and reasoning about the model that one makes progress on coming to understand the phenomenon/phenomena of interest.9

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9A major caution about the business of categorizing: We do this for the purpose of discussion and because we believe that a consideration of these different cognitive aims is potentially fruitful in the context of education. However, whenever something is presented in a list of categories, a
The challenge with depicting something as an iterative cycle is that it is difficult to know where to begin in discussing it. We do begin with an assumption from cognitive science that in general reasoning is “theory laden” or model based (Vosniadou 2001). Humans are incapable of interacting with ideas or other stimuli without simultaneously doing some level of integrating of those inputs into the cognitive architecture that is already present. In this sense, the cognitive agent does always begin with a model, although it is often implicit.

This does not imply, however, that instruction must always begin with an explicit model. Quite often instruction may begin with a puzzling phenomenon or an interesting data pattern. It may even begin with an explanation or prediction. However, at some point in the instructional sequence, the model must be drawn out in explicit ways so that its full potential as a reasoning tool can be realized.

### 36.3.1 Reasoning with Models

A major class of reasoning with models is to use them as filters on the world that serve to constrain and bound the problem space. This role of the model is in line with Odenbaugh’s exploratory vision of model use (2005). What it is exactly that one finds intriguing about a particular phenomenon is wholly dependent on the model that the phenomenon is examined through. For example, when examining certain physical attributes of an organism, one may be interested in and attend to the genetic basis of a particular trait if the phenomenon is viewed through the lens of genetics models. Alternatively, one might be interested in the selective advantage of that trait in a particular environment if the phenomenon is viewed through the lens of evolutionary models.

An outcome of this kind of reasoning can be a particular description of the phenomenon. In one sense this is a representational task, but prior to any representation, the observer must bound and filter what it is that is worth noticing. This is done with regard to the model and is often the first stage in the sense-making process: defining what it is exactly that is of interest. In educational contexts, this stage is often done for the students prior to instruction in that the articulated learning goals imply a focus on specific models. To return to the example of organism traits, the way in which those traits are defined or described will vary depending on whether the students are supposed to be learning genetics or evolutionary models.

In the process of making sense of what is observed, one typically interacts with the world in particular ways. In figuring out how to manipulate and generate information from the world, one is guided by a current understanding of how the system functions. Interventions are based on models and an explicit attention to them can clarify what it is one wants to know more about and why that information may be common interpretation is that that format implies an order. This is not our intention. The point here is that models organize a broad array of cognitive aims beyond representing and explaining which seem to be the two most commonly associated with models (Odenbaugh 2005; Knuuttila 2005).
useful in attaining a higher-order goal of sense-making. Reasoning with a model often points to areas that need further exploration and allows scientists to ask meaningful questions. From these questions, then, a scientist can derive and carry out investigative plans whether those involve data collection or simulations.

Two studies by Metz suggest that the degree to which there is an explicit focus on an underlying model may alter the degree to which students can productively engage in generating meaningful questions and investigations. Metz (2004) reports on a classroom study of elementary school children (second and fifth graders) designed to support the children in articulating and designing their own inquiries. Students had the opportunity to observe crickets and were able to generate many questions about them, but, according to Metz, few of them were scientific (e.g., What different crickets like different foods? What color do crickets seem to prefer? Where would crickets go on the playground?) (Metz 2004, p. 240). Metz does not interpret lack of scientific sophistication of these questions as attributed solely to students’ age but rather to a lack of curricular support around question generation. In fact, some students did come up with potentially meaningful scientific questions (e.g., Where do crickets spend their time, in the shade or in the sunlight?) suggesting that students did have some scientifically interesting ideas about crickets but that they may have lacked the support needed to make those questions meaningful, reflecting “the failure of this initial version of the animal behavior curriculum to systematically scaffold theory-building” (Metz 2004, p. 267).

In contrast, Metz (2008) describes a classroom vignette in which students engage in thought experiments to explain the phenomenon that ants walk along the same line to get back to their nest. The focus of this activity was on generating plausible explanations for this phenomenon and then using those tentative explanations to develop a research question that could be tested. Students’ tentative explanations were simple models with a relatively small number of constructs and relationships (e.g., ants are detecting some smell in the environment to lead them back to the nest). With these ideas explicitly articulated, the students could focus on attending to how they would collect evidence to support or refute various possibilities. For example, when one set of students devised a broom test that would sweep away the trail, other students could critically evaluate that suggestion in light of the emerging smell model by considering whether or not smell was something that could be removed with a broom. In these two studies, the difference between a focus on sensemaking and question generation in absence of a larger sense-making aim illustrates the potential importance of reasoning with a model and in making that explicit in the classroom.

When scientists reason with the model to carry out thought experimentation, they consider “how possibly” something might work. As Odenbaugh points out, this may involve adding particular conceptual elements to the broad framework which then find their way into the model itself. Scientists may then use their current models to develop explanations for how a system might work or to make predictions about the future behavior of that system.

In a study by Berland and Reiser (2011), students use simulation output of an ecological system containing organisms at three trophic levels (fox, rabbit, and grass)
to determine the trophic level of a fourth unknown invading organism. In this report on the curriculum, it seems that the model that governed the simulation was largely implicit. This is an example where explicit attention to the underlying ecological models may have altered the student discourse during this activity. The students were engaged in sensemaking, but because the model was not made explicit, an important tool for that sensemaking aim was invisible in the classroom discourse. The primary resource the students had for defending claims was the data representation itself.

Berland and Reiser report on how students were engaged in trying to present arguments in support of their preferred claims. For example, one student countered another student’s claim that the invader eats rabbits by explicitly referring to the graph: “you claim that the invader eats rabbits, right? Well, at the end of the graph when the rabbits are dead, how do the invader keep going up?” (Berland and Reiser 2011, p. 202). Underneath the first student’s claim that the invader eats rabbits is a model in which the invasive organism shares a trophic level with the fox. Making sense of what this implies could have been supported by first developing a robust understanding of the three organism system and then reasoning through what could possibly happen if an invader was added to the system. This kind of thought experimentation with an explicit focus on the model at work behind the scenes of the simulation may have allowed the students to interpret the invader data more clearly. Such a model would explicitly link population numbers in the fox to the abundance of its food source, rabbit, and would make the prediction that if the rabbit population were to decrease, we would expect a decrease in the fox population as well. Being able to imagine how the system might change in response to changes in variables could help students make theoretically justified claims that they could then hold up against the simulation output.

The operations and outcomes of reasoning with models depicted in Fig. 36.3, collectively, are at the core of sense-making. That is, if a phenomenon is thoroughly described, investigated, and explained, then it has been reduced to some kind of order, or it has been made sense of in the broadest sense. Reasoning with a model is core to the scientific practices of observing, describing, asking questions, designing investigations, explaining, and predicting.

### 36.3.2 Reasoning About Models

Reasoning about models refers to the integrated practices of developing, evaluating, and revising models. In Fig. 36.3, reasoning about models means making decisions about how to synthesize ideas from a number of different sources in the service of more clearly articulating a model. Boumans (1999) makes the important claim that this work is done iteratively and concurrently with model use and so, again, recalls that these different cognitive strategies are teased apart in the diagram for the purposes of discussion.
Reasoning about a model involves making and justifying a number of decisions. One major class of model-based reasoning involves making representational decisions (Nersessian 2002; Knuuttila 2005). In order to share a model within a community of practice, the model must be externalized in some way. The types of things a scientist attends to in creating these externalizations are often central to the formulation of the model itself. For example, if one chooses to represent a model in mathematical form, there are a range of decisions one must make about how different aspects of the model are laid out and the precise ways that each model idea, as represented in a mathematical expression, relates to others. Then, once a mathematical model is analyzed or a computational model is run, the scientist must interpret the results using the initial framework, checking to see if the model output makes sense and is useful in figuring out something about the system under study.

In an undergraduate context, Svoboda and Passmore describe how the question and the model coevolved over time (2011). Specifically, students in this context were attempting to model vaccination-disease dynamics. The students never had a firm hypothesis that they were attempting to prove or disprove. Rather, the group was engaged in a creative and dynamic process of trying to make sense of a complex phenomenon. Throughout the course of their months-long inquiry, they spent a lot of time reasoning about the model with close attention to their initial intentions for modeling the system. They had been inspired to undertake this particular project after reading an article that described how media attention about a possible link between autism and the measles, mumps, and rubella (MMR) vaccine led to reduced vaccination and recent disease outbreaks in countries that have voluntary vaccination strategies.

As they went about their work, they continually returned to their initial goal of making sense of the phenomenon of disease-vaccine dynamics. This attention allowed them to make a series of decisions about what to include in their model, how to represent various aspects of the system, and how to interpret results of their modeling activities.

In the process of crafting a specific articulation of a model and communicating it to others, it is not uncommon to come across aspects of the model that need further expansion. Odenbaugh (2005) delineates this as a process of conceptual development. Deciding on, describing, and defining the working pieces of the model are all involved at this point.

Another class of reasoning about the model comes when one considers the relationship between particular phenomena and models. Often, a model is developed in the context of examining a very specific phenomenon. For example, one might model the relationships between a set of organisms in a particular environment. Doing so, by necessity, involves attending to the specific details of those organisms in that environment. The model may be deemed useful for explaining one very specialized situation, but from there one might wonder if the model could be applied to other similar phenomena. So, another way in which reasoning about the model occurs is to consider the generalizability of a particular model. One aspect of this may be to make representational decisions about how to broaden the model focus beyond a particular phenomenon to make it useful to explain a larger class.
To come back to the intertwined issues of “discovery and justification” (Boumans 1999), it is in the process of thinking explicitly about the model that model development and evaluation come together. Iterating between model use and meta-level processing about the extent to which the model is achieving one’s aims is at the core of evaluating a model. The scientist reasons with a model to develop explanations and/or predictions and from there considers whether those knowledge products are useful or not. If not, it may be necessary to consider if the issue is related to the model itself, thus suggesting a need for revision, or if it is an issue of translating the model into an explanation that is at play.

In all cases, issues around reasoning about the model must be inextricably tied to the intention of the modeler. There is no context-free way to make reasonable decisions about the attributes and form of a model. These decisions, in practice, must always be made with regard to the purpose the model is put to in the context of its use.

A study by Hmelo-Silver and Pfeffer illustrates this point. They describe how students had trouble constructing models of aquaria that extended beyond superficial structural features, while experts tended to include deeper functional relationships (Hmelo-Silver and Pfeffer 2004). One way to understand this difference is to ask how each of these groups interpreted the purpose of this model development task. It is clear that experts brought a particular set of aims and purposes to the task. For example, expert aquarium hobbyists were concerned with the aim of maintaining healthy fish and tended to include variables and the relationships among variables in aquaria that are related to fish health. In contrast, ecologists constructed models that could be used to explain ecosystem stability over time.

That students attended to surface features suggests that they viewed the task as primarily descriptive (i.e., they were supposed to be building models of aquaria). Rather than propose that students are not as good as experts at attending to deeper features, this as an example where the students needed additional scaffolding around the purpose of model development.

While this work is important because it gave students the opportunity to take responsibility for model development, without an explicit aim, students had no way to productively bound what they were modeling or make decisions about what to include and what to leave out. If instructors do not make the purpose of a modeling activity clear to students, they will bring their own frame to it, and that framing, without explicit attention, may be idiosyncratic rather than shared across the group. If model development and justification cannot be decoupled, then there is simply no robust way to engage in model development in the classroom in the absence of a clear aim that can guide the evaluation/justification of the model.

In contrast, Smith and colleagues (1997) describe how groups of ecology students constructed models relevant to an aphid-wasp-fungus system. Crucially, prior to constructing models, the students were first asked to develop questions that they were interested in investigating. The students were then able to make decisions about the degree of detail and complexity to add into their models. Different groups of students, depending on the question they proposed and the aims they prioritized, then constructed very different models.
A growing number of scholars have written about the importance and utility of allowing students to construct and critique models.\textsuperscript{10} What the science studies lens brings to such environments is the importance of coupling model development and evaluation to a clear sense-making aim. In order for students to make the appropriate decisions about how to bound and describe a system, they need to have a clear sense of what the model will ultimately used to do.

What these examples are meant to draw out is how, when contextualized in this way, the practices of constructing, representing, evaluating, and revising models can support productive sensemaking work. These examples highlight how reasoning about models is inextricably linked to considerations of what those models can then be used to do. Thus, reasoning \textit{about} the model is done with critical attention to the output of reasoning \textit{with} the model to achieve a particular aim. When these practices are not linked in instructional settings, then the outcome may not realize the full potential of model-based reasoning in supporting learning.

\section*{36.4 Major Implications and Recommendations}

\subsection*{36.4.1 Implications}

To consider a view of the various aims that a modeler can have and pay explicit attention to the two major classes of model-based reasoning identified above has implications for the way in which science educators approach science instruction and the degree of student ownership and autonomy. Moreover, a focus on models provides a framework in which the various practices of science can be organized and put to productive use in the classroom.

Much has been made over the past few decades about teaching for conceptual change. As part of this approach, many science educators have been involved in determining a canon of scientific ideas. What if the criteria for what counts as the canon were shifted? Obviously scientists do not undertake their cutting-edge work aiming at an established canon of models. To present the task in science classrooms as one in which the students are trying to uncover or guess the canonical model seems disingenuous at best. Maybe there is, however, a canon of classes of phenomena that a scientifically literate student should be able to explain, and those explanations are based on a developmentally appropriate set of models. In this way instruction could actually be crafted authentically, and the intellectual environment of the classroom could reflect the particular sensemaking aims of the community of learners at any given time while concurrently fostering deep understanding of important science concepts.

\textsuperscript{10}See, for example, Baek et al. (2011), Clement (1989, 2000), Gilbert et al. (1998a, b), Hogan and Thomas (2001), Passmore and Stewart (2002), Schwarz et al. (2009), Svoboda and Passmore (2011), and White (1993).
As students engage in the kind of reasoning described here, they should develop a greater sense of ownership over ideas as they develop them iteratively to address specific reasoning aims that their classroom community has identified. Many of the studies cited above bear witness to the fact that students will engage in complex reasoning when tasks are designed that require it. By organizing these tasks in explicit ways with regard to reasoning with and about models, students may develop a sense of autonomy and begin to demand learning environments that are fundamentally about figuring things out about how the world works.

The framework presented here unites and organizes a number of practices that science educators have been focused on for the past several years (NRC 2007, 2011). The centrality of models to the practices of asking questions, designing investigations, developing explanations, and arguing from evidence becomes clear for both students and teachers. Sadly, higher-level goals of science do not seem to drive science education which tends to focus on the practices in ways that are potentially isolated from higher-order sensemaking goals of explanation (Metz 2006). Placing a model-based view of science at the center of the practices has the potential to counter the treatment of each practice as isolated and unite them in service of sense-making.

### 36.4.2 Research Recommendations

From the view of models in science presented here, there are a number of research avenues for investigating how models operate in learning science. In Sect. 36.3 we explored the real or imagined role of an explicit focus on models in learning environments that have been described in the science education literature. However, more detailed work is needed in this area to understand exactly how a focus on models and modeling interacts with learning both the conceptual content of particular scientific disciplines and how it may influence students’ epistemological views. A recent article by Eve Manz (2012) is one example of this type of scholarship.

If the field can agree on a set of guiding principles for what modeling entails in science learning, then a series of deep investigations into learning environments will be possible that simultaneously attend to the particulars of each context and provide insights into a broader framework. As it stands now, there is a wide range of conceptualizations around modeling and its relationship to other scientific practices, and thus, it is sometimes difficult to understand how different studies speak to one another.

Further, there will need to be additional research on teacher conceptualizations and enactments around model-based inquiry. This work is underway,\(^\text{11}\) but it is clear that teachers (both preservice and in-service) have had very little experience with a view of science as a model-based enterprise and thus may be challenged to enact

\(^{11}\)See, for example, Danusso et al. (2010), Nelson and Davis (2012), and Schwarz and Gwekwerere (2006).
model-based curricula (Windschitl et al. 2008a). As researchers uncover and delineate some of the challenges teachers face in supporting students in model-based inquiry, additional resources can be developed to support teachers, including comprehensive curriculum.

36.5 Conclusion

This chapter was crafted to answer questions about the function of models in science and how that view could be translated for educators. The practice turn in science studies has been fruitful in focusing the scholarly community on the importance of models and in identifying the particular ways in which models function in the intellectual lives of scientists. The science studies’ work has informed science educators and the time has come to more fully incorporate the findings from philosophical, historical, and cognitive studies of science into science education.

So, in the end we are hoping to make what may seem a subtle shift but one we find incredibly important and powerful in thinking about science education. Instead of listing the kinds of models there are and arguing about what the canonical set of target models for instruction might include, we suggest that the dialogue becomes one that is centrally about the context-dependent roles that models are playing in the students’ reasoning/sense-making about phenomena. In making instructional and curricular decisions based on a “models for” orientation, we expect a more productive and hopefully authentic version of school science to emerge.

If it is relatively uncontested that models form the basis of most reasoning in science, then it seems obvious that they should form the basis of reasoning in science classrooms. And, although this is often the case when we examine productive classroom activity, the models are rarely made explicit. There may be much to be gained from changing this state of affairs, but ultimately that is an empirical question. The presence of and attention to models as used by cognitive agents for specific purposes both focuses and organizes the cognitive activity that is primarily aimed at sense-making. As science educators take seriously the “practice turn” and call for authenticity, it will be a central focus not only on models but also on what they are being used for in the sense-making process that will provide a way forward.

References


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