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ARTICLE

'Models of' versus 'Models for'

Toward an Agent-Based Conception of Modeling in the Science Classroom

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Abstract The inclusion of the practice of "developing and using models" in the *Framework for K-12 Science Education* and in the *Next Generation Science Standards* provides an opportunity for educators to examine the role this practice plays in science and how it can be leveraged in a science classroom. Drawing on conceptions of models in the philosophy of science, we bring forward an agent-based account of models and discuss the implications of this view for enacting modeling in science classrooms. Models, according to this account, can only be understood with respect to the aims and intentions of a cognitive agent (models for), not solely in terms of how they represent phenomena in the world (models of). We present this contrast as a heuristic—*models of* versus *models for*—that can be used to help educators notice and interpret how models are positioned in standards, curriculum, and classrooms.

Keywords Modeling · Epistemic agency · NGSS · Philosophy of science

1 Introduction

The vision of science education put forward in the *Framework for K-12 Science Education* and the *Next Generation Science Standards* (*NGSS*) in the USA calls for students to engage in eight science and engineering practices (NGSS Lead States 2013; NRC 2012) as part of their educational experience. Rather than separately learning the content, process and epistemology of science, the *Framework* calls for integration, where knowledge is developed and refined through practice with regard to context-dependent epistemic considerations (Osborne 2014). As many have argued, this new vision of science education calls for inviting students to participate in science rather than just learn about it (e.g., Schwarz et al. 2017). In order to

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participate in science, students need to be positioned as constructors and evaluators of scientific knowledge—in other words, as epistemic agents (e.g., Berland et al. 2016; Ford 2008; Manz 2012; Stroupe 2014). Like scientists who operate within a community of practice with its own set of epistemic aims and criteria (Knorr-Cetina 1999), enacting the Framework vision is about creating science classroom communities that allow students to grapple with the complexities of proposing, pursuing, and refining scientific aims.

This vision requires a significant shift from the epistemic culture dominant in school science classrooms that typically asks students to reproduce knowledge from authority (Duschl 2008). While the Framework calls for students to explore and refine knowledge as a community, the perceived pressure to cover the specified core ideas can undermine students' epistemic agency. This is not a new tension; it is one that has plagued calls for inquiry-based instruction more broadly (Gilbert et al. 1998; Grandy and Duschl 2007; Hammer et al. 2008; Schwab 1960; Sikorski et al. 2009).

We see the tension between content coverage and epistemic agency as particularly problematic for enacting the practice of "developing and using models." One reason for this is the ambiguity around the term "model" in science education and within science itself. The ambiguity by itself is not the problem; rather, it is that some versions of the term are less able to support students' epistemic agency in doing science because they tend to treat models as representations of what is known rather than as tools to be used in generating new knowledge.

Consider, as an introductory example, the following statements about the activity of students in two learning environments:

> Statement 1: In their biology classroom, students built a model of DNA.
> Statement 2: In their biology classroom students developed a model for explaining how genetic information is copied and transmitted in living things.

It is easy to imagine how the first statement could play out in a classroom. Students would build a molecule using paper or pipe cleaners. They might be instructed to create a double helix, to match up the base pairs according to rules or shapes provided by the teacher, or to show how the bases are linked with different numbers of hydrogen bonds. The focus of this activity would be on *depicting* what the DNA molecule looks like—its component parts and the structural arrangement of those parts. This is an activity about demonstrating what is known about DNA, and students are likely to understand the object they are building and the details about its structure as the thing they should know. In a lesson like this, knowing the structure of DNA is a goal unto itself; it does not serve a larger epistemic aim as it did for those original modelers of this molecule, Watson and Crick.

Watson and Crick's elucidation of the structure of DNA was embedded within a scientific pursuit of understanding how a molecule could encode genetic information, replicate itself with fidelity, and pass that information from one generation to the next. As is evident in Crick's letter to his son written days before publication of their findings:

> You can now see how Nature makes copies of the genes. Because if the two chains unwind into two separate chains … In other words, we think we have found the basic copying mechanism by which life comes from life.[1]

[1] This letter, sent to Crick's son Michael in 1953, was printed in the New York Times in 2013: http://www.nytimes.com/interactive/2013/02/26/science/crick-letter-on-dna-discovery.html?_r=0

In a classroom based on the second statement above, the material activity might look much the same. Students could be given the building blocks of DNA to manipulate and arrange. However, in this scenario, they would not simply build a DNA molecule for its own sake. Instead, they could be tasked with constructing a molecular object with the capacity to store and replicate information. Students could propose what properties such a molecule would need to have and consider what structural arrangements could allow a molecule like DNA to copy information as cells divide. By situating the model building within this larger search for an explanation for a phenomenon, the models students would generate could do work for them—helping them think about why DNA is structured the way it is. Alternative models could potentially raise new questions about whether other molecules could plausibly play the same role and why they do not. Students' ideas about DNA could be evaluated in the context of this use rather than solely through comparison to established facts. Initial models that explain DNA's replication mechanism could next be evaluated against new criteria, such as the ability of the molecule to fold up inside the cell nucleus.

Return to the statements above and notice the use of prepositions following the word model. We use these prepositions "of" and "for" as shorthand for two alternative conceptions of the word model.[2] To continue with the DNA example, *models of* focuses attention on the mapping between the real molecule and its representation, whereas *models for* shifts attention to how the component parts and relationships included in the model serve an epistemic purpose beyond depiction. We want to be clear that it is not the prepositions themselves that need revision. Models will continue to be described as *of* objects, systems, or phenomena, as this naming system has been a convenient way to index them. Nevertheless, we want to draw explicit attention to how the idea of models *of* creates a false sense that there exists a set of models that simply map onto the real world in some one-to-one way—that on the one hand, there is real DNA and on the other, there is our model of DNA. Instead, we wish to emphasize the ways in which models are built and used in science as tools that support inquiry and exploration. We therefore introduce the contrast between models *of* and models *for* as a heuristic that provokes consideration of how models are used. While it is true that "a model is always *of* some things and *for* a specific purpose." (Halloun 2007, p. 22, emphasis in the original), too often models make their way into science classrooms in ways that focus entirely on their representational nature (what they are of) and exclude any reference to their epistemic function (what they are for).

Creating classroom environments in which students are participating in science by collectively developing and monitoring shared epistemic aims requires significant instructional work (e.g., Damşa et al. 2010; Stroupe 2014). Helping teachers enact this shift will require much more than a shift in the way we define and use the term "model." Yet we do believe that the definition and attention to how the word is used is necessary: in order for modeling to support student engagement in scientific practice in science classrooms, models must be understood as tools for inquiring, not as representations of what is known (Passmore et al. 2014). We intend the contrast between *models of versus models for* to be used as a heuristic device to help educators notice and interpret how models are positioned in standards, curriculum, and classrooms.

In the next section, we review the origins of the of/for contrast in the philosophy of modeling literature by tracing the trajectory of the two conceptions. We then present an

[2] Our use of *models of* and *models for* is similar to but distinct from that of Keller (2000) who uses the terms to bridge theory and experiment in biology, referring to representations of gene pathways in molecular biology as both *of*, in the sense that they represent the mechanisms and *for* in that they generate new questions that motivate future experiments. Our use is also related to Adúriz-Bravo's (2013) use of *model-for* to refer to how models are used to instantiate theory and *model-from*, which like our "of" connotes representation from the world.

elaboration of the *models for* view that positions models as inextricably linked to the agents who use them and the epistemic aims of their scientific practice. We then revisit how the term is used in science education and discuss the implications of the shift from models *of* to models *for* in supporting the practice-based version of science education put forward in the USA by the *Framework* and the *Next Generation Science Standards*.

2 Origins of 'Models of' and 'Models For' in the Philosophy of Science

Historically, a dominant concern of analytic philosophy was to uncover the logical structure of scientific knowledge. Under the paradigm of "logical empiricism", philosophers described theories in terms a syntax comprised of axiomatic statements that mapped onto the observable world through correspondence statements. Because a primary concern of logical empiricists was to elucidate and defend the structure of scientific knowledge, they maintained a clear distinction between knowledge and scientific practice. The work was to formally specify the relationship between theories and the real world, not to worry about the human activity that generated that knowledge.[3]

Beginning in the 1970s,[4] philosophy of science began to undergo a "practice turn" that involved attending to the cognitive and social dimensions of scientific practice. With this turn came an increase in interest around scientific models (Izquierdo-Aymerich and Adúriz-Bravo 2003; Giere 1988; Suppe 1972; van Fraassen 1980). Models, unlike formal theories, could take non-linguistic forms and could represent the world to varying degrees of accuracy (Morgan and Morrison 1999; van Fraassen 1980). The syntactic approach philosophers had applied to theories could not account for the diversity of forms that models could take, and this failure ultimately facilitated its demise. The syntactic view was almost entirely replaced by the semantic or "model-based" view, which defined theories in terms of families of models (Izquierdo-Aymerich and Adúriz-Bravo 2013; Giere 1988; Suppe 1972, 1989; van Fraassen 1980).

For some philosophers, the semantic view raised a new need to understand how to characterize the structural relationship between models and the world. Understanding models as knowledge objects seemed to require understanding how they represent phenomena in the world (Bailer-Jones 2003; French and Ladyman 1999; Frigg 2006). This structural concern is continuous with the earlier aim of describing the structure of scientific theories. It concerns the nature of the mapping between objects in the world and objects in a model. It asks, what are models *of*?

Ultimately, attempts to specify the relationship between models and the world in terms of a structural mapping (isomorphic or partially isomorphic) have not been successful (Downes 1992; Suarez 2003, Suarez 2010). Philosophers have argued that any singular description of the relationship is problematic given that in scientific practice models only partially map onto the world, and different models do so in different ways (Godfrey-Smith 2006; Morgan and Morrison 1999; Morrison 2015; Odenbaugh 2005). These scholars have argued that models must be defined in more context sensitive ways that reflect how they are actually used.[5]With the practice turn, questions about models in philosophy of science have shifted from those

[3] See Giere's (1988) chapter on "Theories of Science" for an elaboration of this history as well as Suppe (1972) for a more detailed history of the rise and fall of logical empiricism.
[4] The practice turn in philosophy of science is often marked by Kuhn's (1970) seminal work.
[5] Downes 1992, Knuuttila (2011), and Suarez (2010) represent strong proponents of a "deflationary" account of models.

about structure to those about the nature and purpose of representation in scientific practice. Rather than focus solely on the structure of models, it has become important to consider their function, raising the question, what are models *for*?

3 Models for a Purpose: An Agent-Based Conception of Models

In the philosophy of science literature, there has been a growing movement to define how models represent with explicit reference to agents and their purposes (Suarez 2002, 2010; Giere 1988, 1994, 2004, 2010; Knuuttila 2005, 2011; Teller 2001; van Fraassen 2010). Giere's initial (1988) solution to the representation problem proposed using the intentionally vague notion of *similarity.* According to Giere, models are similar to the world in certain respects and to various degrees (1988, pp. 107–109) and it is a *cognitive agent* who makes decisions about *which respects* and *to what degree*. As Giere later clarified, "It is not the model that is doing the representing; it is the scientist using the model who is doing the representing" (2004, p. 747). He has called this view, "The Intentional Conception of Scientific Representation," in which an agent intends to use a model to represent the world *for* some purpose (2010, p. 274). That purpose guides the modeling process in ways that influence how scientists construct and evaluate models.

Suarez (2002) introduced a similar version he called the "Inferential account of Scientific Representation." His conceptualization involves two orthogonal dimensions, what Suarez (2010) called a "two vector" notion of scientific representation (p. 97). The first dimension concerns the relationship between model and phenomenon (what the model is *of*) and the second concerns the epistemic aims of the representation's intended use (what the model is *for*). These two dimensions are intertwined so that it is impossible to make sense of what a model of is without understanding what it is for.

Both accounts inextricably link model structure with model purpose. In its fully expanded version then, *models for* stands in for a definition of a scientific model that embeds it in a model-based reasoning system in which a cognitive agent represents a phenomenon with a model in the service of an epistemic aim. Drawing on the work of Giere and Suarez, we have represented two axes that cognitive agents attend to in constructing and using models(Fig. 1). The *representational axis* concerns what the model is of—in what respects and degrees the model represents features of some phenomenon. The *epistemic axis* concerns what knowledge the model is intended to generate—what the model is for. The two axes are interdependent and inform and constrain each other through the linkages between components (the phenomenon, question, model, and epistemic aim). Cognitive agents specify how models will represent phenomena—what models are *of* (vertical arrows) by identifying and bounding phenomena and developing and reasoning with models (external arrows). They do so with attention to an epistemic aim—what the model is *for* (horizontal arrows) by posing questions and generating and refining target knowledge.

In the remainder of this section, we elaborate on how cognitive agents reason with the components of this system, and the linkages among them, during the practice of modeling.

3.1 Agents Bound the World and Define Phenomena with Questions

The natural world does not come pre-packaged and ready to be modeled. The right side of Fig. 1 depicts how an agent must work to carve up the world into a well-bounded

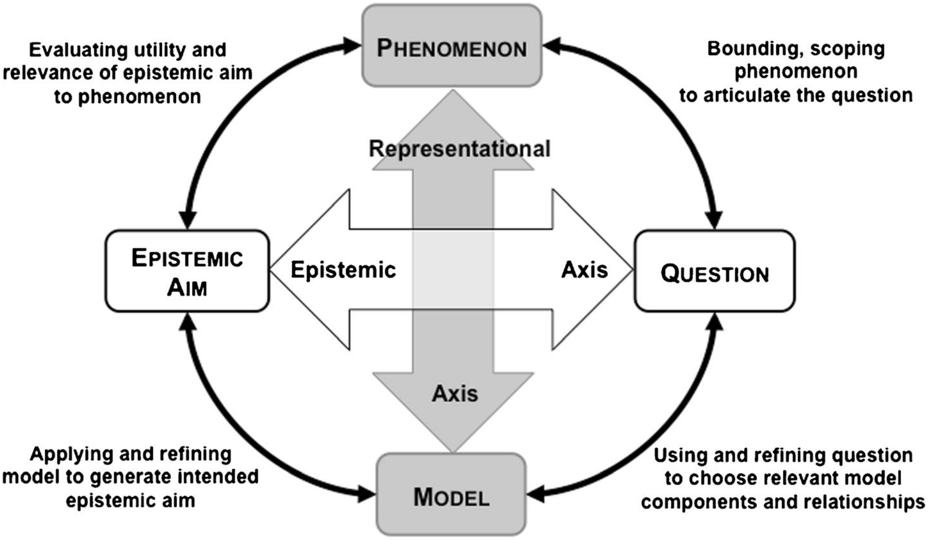

Fig. 1 Agent-based conception of a model defined by the intersection of representational and epistemic axes (*internal arrows*). The cognitive agent acts to keep the components of system in alignment (*external arrows*)

phenomenon. Teller (2010) illustrates the work that needs to be done to turn the world into a phenomenon using the example of listening to an AM radio in a lightning storm.

> [L]ightning produces static in AM radio broadcast signals. Imagine that by carefully analyzing such static we could extract useful information about lightning strikes—how far away, how strong. But now, when considering an AM radio broadcast in a thunderstorm, what constitutes the signal, what the noise? In ordinary situations the causal component generated by the talk that is being broadcast counts as the signal, while the causal component that comes from lighting strikes counts as static—as noise. But if our interest is in the lightning strikes, it is just the other way around. The features of the 'static' caused by the lighting will be our 'signal,' while the component coming from the broadcasted program will be just interfering 'noise' (p. 819).

Phenomena, particularly those with complex causal structures can be noisy. During the modeling process, one role of the cognitive agent is to decide which aspects of the world will be included. While in some sense the model will be of this phenomenon, the ways in which the model represents the phenomenon will be further specified with reference to an epistemic aim.

Listening to the AM radio in a storm, the agent has to decide whether understanding the underlying mechanisms that cause the broadcast signal or the underlying mechanisms that produce an audible static during the storm is the aim. What defines the phenomenon under investigation depends on the interests and intentions of cognitive agents and the particular questions they ask. By deliberately crafting a question about a phenomenon, the cognitive agent focuses on the particular aspect of the phenomenon that he or she will develop a model to interrogate. Questions are an important bridge between the observed and modeled world (Fig. 1). They specify the kind of understanding one is seeking—they help to filter out the noise.

Noticing and characterizing a phenomenon is a critical component of the modeling process—it is how scientists decide what they want their model to be *of*. However, as scientific inquiry proceeds, the boundaries of the phenomenon can expand and contract. Likewise, articulating a question is not a one-time event. And as the question changes, so does what will count as a satisfying answer. In order to keep track of the epistemic aim, cognitive agents have to notice and adjust their activity as questions shift or new questions arise—*of* and *for* shift together.

3.2 Agents Evaluate and Refine Models to Satisfy an Epistemic Aim

Alongside asking questions, agents consider what will count as the type of new knowledge or insight that would help them make progress in addressing their questions. The left side of Fig. 1 depicts how this epistemic aim informs and constrains the modeling process.

The two knowledge targets most commonly associated with modeling are explanation and prediction. We purposely de-identify models with purely descriptive aims—those that focus on representing the system as it is. Description is a critical element of scientific practice that involves identifying and recording the world in detail. While describing the components of a system is a critical part of modeling, it is not sufficient. Modeling is a practice scientists use to learn new things about how the world works by proposing how or why something behaves the way it does (Knuuttila 2005; Morgan and Morrison 1999; Morrison 2015; Nersessian 1999). A model is generative, not merely descriptive.

The knowledge a modeler is seeking will vary in detail and completeness depending on the scope of the question being asked. For example, Craver (2006) described explanations as, "answers to questions about why something has happened or how something works." "Questions and answers," Craver continued, "presuppose a conversational context that specifies precisely what is to be explained and how much detail will suffice for a satisfying answer" (p. 360). It is the role of the modelers, the cognitive agents, to decide what will count as a satisfying explanation or useful prediction. This decision is based on a context-dependent aim (De Regt and Dieks 2005).

While explanations are often associated with accounting for the past, predictions are directed at understanding what can or might happen in the future. In some cases, for some purposes, it is desirable for those predictions to be accurate so that they can guide human action. In other cases, predicting is more about exploring possible alternatives to better understand the relationship between the structure of a model and what it predicts (Svoboda and Passmore 2013). In either case, the kind of knowledge the agent is seeking is what drives the modeling practice.

3.3 Models are Epistemic Tools

Models are not the end-products of modeling—they are the epistemic tools that scientists use to satisfy epistemic aims like explanation and/or prediction (Knuuttila 2011). They are useful tools: cognitive agents use them to externalize and organize their knowledge of a system, allowing them to reason with and evaluate their ideas (Giere 2006; Knuuttila 2005, 2011; Nersessian 1992, 1999, 2002). However, the external representations generated during the modeling process are not equivalent to the model. In scientific practice, models are part of distributed cognitive systems that include cognitive agents, the phenomena they have identified, the questions they have, a model and the desired knowledge they intended for that model to help develop, as well as the larger scientific community within which those models are built and evaluated. When external representations like drawings, graphs, or three-dimensional structures are extracted from the context of modeling, they don't always carry the larger epistemic context with them. Without this context, they can stop functioning as models and instead function as inert knowledge.

Consider the following brief example that illustrates how models have functioned as tools for developing ideas and furthering scientific progress rather than as end-products. The Lotka-Volterra models in population ecology emphasize the way a relatively simple model was used by ecologists to reason about various population phenomena. The Lotka-Volterra model in its simplest form is a pair of logistic equations meant to model the growth of two interacting populations—one predator and one prey. Simberloff (1980) described how the model functioned as a theoretical touch point for decades of work in population and community ecology. For example, the model inspired a line of laboratory work in which simple organismal systems of microbes, beetles, and flies, were used to test the model's predictions about population patterns. In some cases, the model seemed to account for the data well, but in others, revisions and extensions were proposed. For example, Nicholson's experiments using populations of blow flies led him to propose revisions to account for the energy predators must expend in actually processing and consuming prey (e.g., Nicholson and Bailey 1935).

The idea of a coupled logistic growth model was also taken up for different uses. While primarily envisioned as a way to predict population trajectories, others used it to explore relationships among sets of parameters. For example, Park's research explored how changes to the physical environment could change the outcome of competitive interactions (e.g., Park 1948). Others (e.g., Levins 1968) attempted to scale up the original model beyond two populations to account for entire interacting communities, raising questions about the generalizability of these models to larger units of analysis.

By examining this case, it becomes apparent that there is no single "Lotka-Volterra" model of populations. Lotka-Volterra is a suite of models developed over decades by groups of interacting scientists to investigate various questions within population and community ecology. Some versions of these models did yield some new insights about specific populations. But just as importantly, they sparked a conversation within ecology about the kinds of phenomena and questions such models could address and what would count as a satisfying explanation or relevant prediction across these examples.

In this example, the models evolved and changed as new questions were generated and as new aims were articulated. It is an example that shows that models are not simply straightforward mappings of phenomena—they are dynamic tools that offer explanations and predictions up to the community for critique. They also inspire new kinds of questions and new ways of looking at phenomena. Conceptualizing models in this way "attributes the epistemic value of models to their epistemic productivity rather than reducing it to the representation of some pre-existing natural or social systems" (Knuuttila 2005, p. 49). Models are not simply knowledge representations *of* the world they are epistemic tools *for* making sense of the world.

So far, we have described how an agent-based conception of models within philosophy shifted the definition of the term model from a kind of knowledge to a kind of tool embedded within scientific practice. We now link this discussion of models to the uses of models and enactments of modeling in science classrooms.

4 *Models for* and Epistemic Agency in Science Classrooms

For Giere, the importance of an agent in relation to a model reflects his concern with rooting models to the intentions and decisions of a modeler. This move emphasizes that models are human constructions that reflect the knowledge and choices made by a human mind, which Giere meant to contrast with ideas about models as reflecting the inherent logical structure of knowledge. Giere also situated that cognition within a larger community of scientific practice with an evolving set of epistemic concerns and criteria. An agent, or collaborating group of agents, within this community makes decisions about what phenomena are interesting or confusing, what questions are worthy of pursuit, what modeling decisions are acceptable and appropriate and what kind of knowledge will be satisfying (Giere 2006, 2010). This idea of an agent who has the intellectual capacity to act within, and in conversation with, the larger scientific community mirrors recent concerns in the science education literature about the need to support students' "epistemic agency" by engaging them in the intellectual work of science (Berland et al. 2016; Damşa et al. 2010; Stroupe 2014). A *models for* perspective addresses two potential problems for supporting students' epistemic agency perpetuated by a *models of* interpretation.

The first problem concerns equating models with representations of objects or systems. In textbooks and curriculum materials, depictions of objects or systems are commonly referred to as models: the model *of* DNA, *of* the solar system, *of* an atom, *of* the carbon cycle, *of* plate tectonics and are often completely divorced from the phenomena and questions about them that they were developed to explore. Similarly, in an essay arguing for the importance of science practices exemplified in the *Framework for K-12 Science Education* and in the *Next Generation Science Standards*, Osborne (2014) wrote of modeling that:

> Models are needed in science because science deals with things too large to imagine such as the inside of a volcano, the solar system or the phases of the Moon (Gilbert and Boulter 2000). Conversely, models are also needed to represent things which are too small to see such as a cell, the inside of the human body or the atom itself (Harrison and Treagust 2000).

In the quote above, Osborne is clearly describing models as representing the structure of various objects and systems. As we have already elaborated, representation is insufficient to capture the role and utility of models. While the representational role is not the only way models are talked about in the science education community, the *models of* account often comes alongside *models for*, which makes it seem like an alternative on equal footing. Indeed, in this same essay Osborne also discusses a distinct conception of models beyond the "simply representational" (p. 184), as tools that allow *for* explanation and prediction. But what is left underdetermined for the reader is how a model that depicts a cell or an atom is linked to explanation or prediction. It is all too easy for teachers to take up the depictions as ends in themselves. In fact, this interpretation is likely given colloquial understandings of models as scalar representations of objects "too big or too small to see" that are common among science teachers (e.g., Justi and Gilbert 2002, 2003).

In the science education literature, these kinds of representations are sometimes referred to as "pedagogical models" (e.g., Clement 2000; Coll et al. 2005; Gilbert and Boulter 2000; Harrison and Treagust 2000). Pedagogical models are external representations that teachers use to demonstrate and make memorable to students what is known—they are tools that teachers use to explain *to* students. We find it misleading to call these objects models at all. They are more accurately described as representations of content in the form of diagrams, replicas, or illustrations, and they tend to be positioned as targets of instruction for students to acquire. These kinds of depictions can become useful in a modeling endeavor only if they are connected to the epistemic aims of the community that arise from careful examination of phenomena in the world.

This leads to the second major implication of *models for*—to position students as responsible for knowledge construction and evaluation in science classrooms. Part of the solution, as others have argued, is to establish a classroom culture in which students' ideas are elicited and valued, giving students more of a voice (e.g., Stroupe 2014). At the same time, establishing epistemic agency must also involve helping students understand and appropriately apply the epistemic criteria of the scientific community. That is, epistemic agency is about more than who holds authority; it is also about accountability to an organizing disciplinary aim (Ford 2008). “Rather than being left to make their own sense of scientific content as they choose, students should be taught to make *appropriate* sense.” (2008, p. 406, emphasis in the original). That is, students need to be supported in understanding and tracking the epistemic aim guiding their activity. Enacting this version of modeling means establishing communities of practice in science classrooms that are sensitive to disciplinary aims (e.g., Berland et al. 2016; Coffey et al. 2011; Engle and Conant 2002; Ford 2008; Manz 2012; Passmore et al. 2014). For example, Stroupe (2014) described a moment when a teacher allowed the class to pursue a student-generated question about why they observed a drop in body temperature during an exercise activity. In this example, the students were given epistemic agency not only because the teacher positioned their ideas as valuable, but also because the phenomenon (the drop in body temperature), the question (what could have caused this) and the epistemic aim (an explanation) were clear.

5 Implications for Enacting the *NGSS* Vision

The alignment between the disciplinary specific aims and ideas and disciplinary practices is at the heart of the intentions of the *NGSS* vision. Nevertheless, in the descriptors of the modeling practice in the *Framework* and in the Performance Expectations in the *NGSS*, it remains possible, even likely, to interpret models only as models *of.*

Consider a subset of the performance expectations (PEs) intended to assess the practice of “developing and using models” (Table 1). It is easy to see how these statements could be enacted in classrooms in ways that foreground representations *of* objects, systems or processes, divorced from an epistemic aim. As elaborated in Table 1, each has the potential to become an exercise in reproducing canonical representations of systems like the ones often seen in textbooks: illustrating the parts of a cell, the carbon cycle, the rock cycle, the structures of molecules. Reproducing such representations does not reflect the practice of modeling—such activities have no phenomenon, no question, and no epistemic aim. In order to convert such a task into a *model for* task, these elements need to be in place. Switching from a models *of* interpretation to a models *for* interpretation of these performance expectations requires asking the following questions about modeling activities (Fig. 1):

- Is there a clear *phenomenon?* Is there some puzzling or unknown aspect of that phenomenon to investigate? Do students understand their role as trying to understand this phenomenon better?
- Is there a clear *question*? Does the question help clarify what about the phenomenon is puzzling or unknown? Do students understand their role as attempting to answer that question?
- Is there a clear *epistemic aim*? Are there clear criteria for what will count as having made progress toward answering the question? Do students understand themselves to be responsible for generating and evaluating that knowledge?

The *models for* heuristic frames science classrooms as places where *students* get to wonder about and question the world around them. For each of the PEs listed in Table 1, we have

Table 1 A subset of NGSS performance expectations interpreted through the lens of *models of* and *models for*

NGSS performance expectation	*Models of* interpretation	*Models for* interpretation
Develop a model to describe the cycling of Earth's materials and the flow of energy that drives this process. (MS-ESS2-1) Clarification Statement: Emphasis is on the processes of melting, crystallization, weathering, deformation, and sedimentation, which act together to form minerals and rocks through the cycling of Earth's materials	Diagram the rock cycle and indicate which processes require energy	How can we explain the origin of or predict the fate of various geological structures? e.g., What processes could have created the Grand Canyon? What do we predict will happen to it over time?
Develop a model to describe the atomic composition of simple molecules and extended structures. (MS-PS1-1) Clarification Statement: Emphasis is on developing models of molecules that vary in complexity. Examples of simple molecules could include ammonia and methanol. Examples of extended structures could include sodium chloride or diamonds. Examples of molecular-level models could include drawings, 3D ball and stick structures, or computer representations showing different molecules with different types of atoms	Draw or build ball and stick structures of molecules	How can specific properties of various substances be explained? e.g., Why does ammonia have a strong smell? Why is salt visibly cubic? If both diamonds and graphite are made of carbon, why do they have such different physical properties?
Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem. (MS-LS2-3) Clarification Statement: Emphasis is on describing the conservation of matter and flow of energy into and out of various ecosystems, and on defining the boundaries of the system	Diagram the carbon cycle and/or represent relationships in food chains/ webs that illustrate that matter and energy are conserved	How can we explain differences among ecosystems or explain/predict changes over time? e.g., Why are tropical ecosystems more species rich than temperate ecosystems? What happens to a forest after a fire? What is the predicted impact of an influx of fertilizer into a pond ecosystem?
Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy. (HS-PS1-4) Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.	Generate reaction coordinate diagrams or reaction equations that depict how energy changes in a reaction	How can we explain the energetic differences in various reactions? e.g., Why does ice melt when we take it out of the freezer? How does striking a match cause it to light?

Table 1 (continued)

NGSS performance expectation	*Models of* interpretation	*Models for* interpretation
Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms. (HS-LS1-2) Clarification Statement: Emphasis is on functions at the organism system level such as nutrient uptake, water delivery, and organism movement in response to neural stimuli. An example of an interacting system could be an artery depending on the proper function of elastic tissue and smooth muscle to regulate and deliver the proper amount of blood within the circulatory system	Diagram the structures of various body systems (e.g., circulatory system, excretory system)	How can we explain or predict biological functions in terms of underlying structures? e.g., What kinds of structures would a plant need to take up water and distribute that water to cells?
Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection. [HS-ESS2-3] Clarification Statement: Emphasis is on both a one-dimensional model of Earth, with radial layers determined by density, and a three-dimensional model, which is controlled by mantle convection and the resulting plate tectonics. Examples of evidence include maps of Earth's three-dimensional structure obtained from seismic waves, records of the rate of change of Earth's magnetic field (as constraints on convection in the outer core), and identification of the composition of Earth's layers from high-pressure laboratory experiments	Generate representations that depict Earth's layers and patterns of convection within Earth's interior	How can we explain various geologic phenomena, their distribution on Earth and changes over time? e.g., How can we explain the mechanisms that drive plate tectonics? What explains changes in the Earth's magnetic field?
Develop and use a model to describe the function of a cell as a whole and ways parts of cells contribute to the function. (MS-LS1-2) Clarification Statement: Emphasis is on the cell functioning as a whole system and the primary role of identified parts of the cell, specifically the nucleus, chloroplasts, mitochondria, cell membrane, and cell wall	Draw or build a representation that depicts the parts of the cell and label the functions of each part	How do we explain what cells are able to do? e.g., How can we explain the reason for cells' malfunctioning (e.g., cancerous growth)? What structures would a cell need to be able to signal properly to other cells?

provided some examples of phenomena that could be reasoned about using the models mentioned. For example, we asked, what phenomena could “a model to describe the atomic composition of simple molecules and extended structures” (MS-PS1-1) elucidate? What properties of chemical or physical substances could be explained by attending to their atomic structure? What can we predict about the behavior of such substances? By rooting the lesson in these phenomena, students would have the chance to wonder about these things, ask questions about them, and see the need to develop models that could help them deepen their understanding.

Posing specific questions helps students develop a shared motivation needed inform and constrain model development (Fig. 1). When students are asked to “Draw your model of an atom” or “Model the interactions in a lake ecosystem” or “Build a model of DNA,” they have not been provided with enough information about what to do. An exercise in which students are asked to “model a cell” is underspecified. Should they represent all the structures of the cell? Should they favor certain features over others? Without a purpose, students have no criteria against which to judge their own decisions (other than perhaps fidelity to canonical representations). When the question is clear, it can give students a sense of context within which to make choices and justifications that serve a purpose. It is only with this sense of purpose that students can make reasonable, justifiable decisions. If the purpose of modeling is to better understand how a cell is able to divide itself in two, the specific entities and relationships among them can serve a purpose that extends beyond describing a typical cell. Thus, in order to position students as epistemic agents they must be able to either develop, examine or critique the epistemic aims that make a model useful—they should be able to connect to the phenomena and questions that are driving their work.

6 Conclusion

The distinction between *models of* and *models for* reflects an historical tension in the philosophy of science between the structure of models and their function in propelling scientific knowledge and practice forward. We see this same tension mirrored in science classrooms around the implementation of the practice of modeling. In both contexts, conceptualizing models as tools rather than end-products helps us understand the role of epistemic agency in modeling practice.

Ultimately, our point in this article is a simple one. We noted earlier that the contrast between *models of* versus *models for* could be used as a heuristic device to help educators notice and interpret how models are positioned in standards, curriculum and classrooms. More specifically, we have proposed that models can and should enter into science classrooms in ways that position students as epistemic agents who see developing and using models as serving the larger aim of making sense of the world. If, as a community, we can push ourselves to articulate what the modeling work is *for* in our educational designs, we will be a long way toward empowering science students to engage in this practice.

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References

Adúriz-Bravo, A. (2013). A “semantic” view of scientific models for science education. *Science & Education, 22*(7), 1593–1611.

Bailer-Jones, D. M. (2003). When scientific models represent. *International Studies in the Philosophy of Science, 17*(1), 59–74.

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: making scientific practices meaningful for students. *Journal of Research in Science Teaching, 53*(7), 1082–1112.

Clement, J. J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education, 22*(9), 1041–1053.

Coffey, J. E., Hammer, D., Levin, D. M., & Grant, T. (2011). The missing disciplinary substance of formative assessment. *Journal of Research in Science Teaching, 48*(10), 1109–1136.

Coll, R. K., France, B., & Taylor, I. (2005). The role of models/and analogies in science education: implications from research. *International Journal of Science Education, 27*(2), 183–198.

Craver, C. (2006). When mechanistic models explain. *Synthese, 153*(3), 355–376.

Damşa, C. I., Kirschner, P. A., Andriessen, J. E. B., Erkens, G., & Sins, P. H. M. (2010). Shared epistemic agency: an empirical study of an emergent construct. *Journal of the Learning Sciences, 19* (2), 143–186.

De Regt, H., & Dieks, D. (2005). A contextual approach to scientific understanding. *Synthese, 144*(1), 137–170.

Downes, S. (1992). The importance of models in theorizing: a deflationary semantic view. In *PSA: proceedings of the biennial meeting of the philosophy of science association* (Vol. *1992*, pp. 142–153). Chicago: The University of Chicago Press.

Duschl, R. A. (2008). Science education in three-part harmony: balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268–291.

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399–483.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404–423.

French, S., & Ladyman, J. (1999). Reinflating the semantic approach. *International Studies in the Philosophy of Science, 13*(2), 103–121.

Frigg, R. (2006). Scientific representation and the semantic view of theories. *Theoria, 55*, 49–65.

Giere, R. N. (1988). *Explaining science: a cognitive approach*. University of Chicago Press.

Giere, R. N. (1994). The cognitive structure of scientific theories. *Philosophy of Science, 61*(2), 276–296.

Giere, R. N. (2004). How models are used to represent reality. *Philosophy of Science, 71*, 742–752.

Giere, R. N. (2006). The role of agency in distributed cognitive systems. *Philosophy of Science, 73*(5), 710–719.

Giere, R. N. (2010). An agent-based conception of models and scientific representation. *Synthese, 172*(2), 269–281.

Gilbert, J., & Boulter, C. (Eds.). (2000). *Developing models in science education*. Dordrecht: Kluwer.

Gilbert, J. K., Boulter, C., & Rutherford, M. (1998). Models in explanations, part 2: Whose voice? Whose ears? *International Journal of Science Education, 20*(2), 187–203.

Godfrey-Smith, P. (2006). The strategy of model-based science. *Biology and Philosophy, 21*(5), 725–740.

Grandy, R. E., & Duschl, R. A. (2007). Reconsidering the character and role of inquiry in school science: analysis of a conference. *Science & Education, 16*(2), 141–166.

Halloun, I. (2007). Mediated modeling in science education. *Science & Education, 16*(7), 653–697.

Hammer, D., Russ, R., Mikeska, J., & Scherr, R. E. (2008). Identifying inquiry and conceptualizing students' abilities. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching scientific inquiry: recommendations for research and implementation* (pp. 138–156). Rotterdam, NL: Sense Publishers.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education, 22*(9), 1011–1026.

Izquierdo-Aymerich, M., & Adúriz-Bravo, A. (2003). Epistemological foundations of school science. *Science & Education, 12*, 27–43.

Justi, R., & Gilbert, J. K. (2002). Science teachers' knowledge about and attitudes towards the use of models and modelling in learning science. *International Journal of Science Education, 24*(12), 1273–1292.

Justi, R., & Gilbert, J. K. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*(11), 1369–1386.

Keller, E. F. (2000). Models of and models for: Theory and practice in contemporary biology. *Philosophy of Science, 67*(S1), S72–S86.
Knorr-Cetina, K. (1999). *Epistemic cultures: how the sciences make knowledge*. Harvard University Press.
Knuuttila, T. (2005). Models, representation, and mediation. *Philosophy of Science, 72*(5), 1260–1271.
Knuuttila, T. (2011). Modelling and representing: An artefactual approach to model-based representation. *Studies in History and Philosophy of Science Part A, 42*(2), 262–271.
Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: University of Chicago Press.
Levins, R. (1968). *Evolution in Changing Environments.* Princeton, NJ: Princeton University Press.
Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071–1105.
Morgan, M. S., & Morrison, M. (1999). Models as mediating instruments. In M. Morrison & M. S. Morgan (Eds.), *Models as mediators. perspectives on natural and social Science* (pp. 10–37). Cambridge University Press.
Morrison, Margaret. (2015). *Reconstructing reality: models, mathematics, and simulations*. Oxford University Press.
National Research Council. (2012). *A framework for K-12 science education: practices, crosscutting concepts, and core ideas*. Washington DC.
Nersessian, N. J. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. *Cognitive models of science, 15*, 3–44.
Nicholson, A. J. & Bailey, V. A. (1935). The balance of animal populations. *Proceedings of the Zoological Society of London, 3,* 551-598.
Nersessian, N. J. (1999). In L. Magnani, N. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in conceptual change* (pp. 5–22). New York: Kluwer Academic/Plenum Publishers.
Nersessian, N. J. (2002). The cognitive basis of model-based reasoning. In *The cognitive basis of science* (pp. 133–153). Cambridge University Press.
NGSS Lead States. (2013). *Next generation science standards: for states, by states*. Washington, DC: The National Academies Press.
Odenbaugh, J. (2005). Idealized, inaccurate but successful: a pragmatic approach to evaluating models in theoretical ecology. *Biology and Philosophy, 20*(2–3), 231–255.
Osborne, J. (2014). Teaching scientific practices: meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177–196.
Park, T. (1948). Experimental studies of interspecies competition. I. Competition between populations of flour beetles, *Tribolium confusum* Duval and *Tribolium castaneum* Herbst'. *Ecological Monographs, 18,* 265–307.
Passmore, C., Gouvea, J. S., & Giere, R. N. (2014). Models in science and in learning science: focusing scientific practice on sense-making. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching*. Springer.
Schwab, J. J. (1960). Inquiry, the science teacher, and the educator. *The School Review, 68*(2), 176–195. doi:10.2307/1083585.
Schwarz, C., Passmore, C., & Reiser, B. (Eds.). (2017). *Helping students make sense of the world using next generation science and engineering practices*. Arlington: NSTA Press.
Sikorski, T., Winters, V., & Hammer, D. (2009). Defining a learning progressions for scientific inquiry. In Learning Progressions in Science (LeaPS) Conference. Iowa City, IA.
Simberloff, D. (1980). A succession of paradigms in ecology: Essentialism to materialism and probabilism. *Synthese 43* (1), 3-39.
Stroupe, D. (2014). Examining classroom science practice communities: how teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education, 98*(3), 487–516.
Suarez, M. (2002). An inferential conception of scientific representation. *Philosophy of Science, 71*(5), 767–779.
Suárez, M. (2003). Scientific representation: Against similarity and isomorphism. *International Studies in the Philosophy of Science, 17,* 225–244.
Suarez, M. (2010). Scientific representation. *Philosophy Compass, 5*(1), 91–101.
Suppe, F. (1972). What's wrong with the received view of the structure of scientific theories? *Philosophy of Science, 39*(1), 1–19.
Suppe, F. (1989). *The Semantic Conception of Theories and Scientific Realism*. Urbana: University of Illinois Press.
Svoboda, J., & Passmore, C. (2013). The strategies of modeling in biology education. *Science & Education, 22*(1), 119–142.
Teller, P. (2001). Twilight of the perfect model model. *Erkenntnis, 55*, 393–415.
Teller, P. (2010). "Saving the phenomena" today. *Philosophy of Science, 77*(5), 815–826.
van Fraassen, B. (2010). Scientific Representation: Paradoxes of Perspective. *Analysis 70* (3), 511–514.
van Fraassen, B. (1980). *The scientific image*. Oxford: Oxford University Press.