ABSTRACT: Scientific explanation plays a central role in science education reform documents, including the *Benchmarks for Science Literacy*, the *National Science Education Standards*, and the recent research report, *Taking Science to School*. While scientific explanation receives significant emphases in these documents, there is little discussion or consensus within the science education community about the nature of explanation itself. However, debates about scientific explanation have been a mainstay for philosophers of science for decades. We argue that a more clearly articulated conceptualization of scientific explanation for science education is necessary for making the vision of science education reform a reality. In this essay, we use major philosophical theories of scientific explanation as lenses to examine how the science education community has constructed the idea of
explanation. We also examine instructional practice in school science settings, including our own classrooms, where teachers and students are working to explain natural phenomena. Using these examples, we offer suggestions for preparing both educators and young learners to engage in explanatory discourses that are reasonably accountable to authentic epistemic practice in science. © 2011 Wiley Periodicals, Inc. *Sci Ed* 1–31, 2011

**INTRODUCTION**

Science educators engaged in reforming science education envision classrooms where students and teachers focus on key ideas and practices in science especially through the construction and understanding of scientific explanations (American Association for the Advancement of Science [AAAS], 1993; Harrison & Treagust, 2000; Millar & Osborne, 1998; Mortimer & Scott, 2003; National Research Council [NRC], 1996, 2007; Osborne & Dillon, 2008; Treagust & Harrison, 2000). This press for explanation is believed to be crucial for engaging students in some of the most central epistemic practices of science and for developing robust understanding (Chinn & Malhotra, 2002; Duschl & Grandy, 2008; Driver, Asoko, Leach, Mortimer, & Scott, 1994; Windschitl, 2008). Unfortunately, within the field of science education “scientific explanation” is not well defined for educational researchers, classroom teachers, and ultimately for science students. While there are many scholars in science education working to support teachers’ and students’ efforts at pressing for scientific explanations, the projects are often undertheorized with regard to scientific explanation. The lack of clear vision and definition about the substance and function of scientific explanations leaves teacher educators like us and the early career teachers with whom we work struggling to support students’ work with scientific explanations.

The current practice of many experienced teachers tends to focus on students accumulating and repeating descriptive information about natural phenomena and engaging students in observational exercises or rudimentary experiments without pressing students toward scientific explanations of phenomena (Banilower, Smith, Weiss, & Pasley, 2006; NRC, 2007; Osborne & Dillon, 2008; Roth & Garnier, 2007). In order for science educators to be able to encourage young students to make shifts from descriptions to explanations in science classes, we must provide more guidance about the nature of scientific explanations and more insight into how teachers and students can generate and evaluate scientific explanations. This is not merely an exercise in terminological precision. While clarity of language and meaning is instrumental for communication and development of new ideas, more important to the field of science education is a shared vision of what kinds of learning are possible in classrooms, how these articulate with authentic disciplinary practices, and how these can be scaffolded in principled ways for students.

Philosophers of science have long examined the structure and role of explanation in the sciences beginning with the seminal work of Hempel and Oppenheim (1948) and spanning the subsequent contributions of Salmon (1978, 1989), Van Fraassen (1980), Friedman (1974), Kitcher (1989), and others. This body of work offers lenses for analyzing how scientific explanations are constructed in science and how science educators might design learning environments to foster scientific explanation with students in secondary classrooms. We use the major models of scientific explanation from the philosophy of science literature to engage with four questions:

1. How is scientific explanation defined within philosophy of science?
2. How has research in science education classrooms framed and supported scientific explanation?
3. How have science education reform documents framed scientific explanation?
4. How has our research project supported teachers’ and students’ work with scientific explanations over the past four years?

FIVE MODELS OF SCIENTIFIC EXPLANATION FROM PHILOSOPHY OF SCIENCE

Philosophers of science have spent decades analyzing both the process of constructing explanations and the merits of existing scientific explanations themselves. There is no unitary theory of explanation in philosophy of science, but there are some areas of general agreement. Many philosophers of science broadly conceptualize scientific explanations as attempts to move beyond descriptions of observable natural phenomena into theoretical accounts of how phenomena unfold the way they do (Achinstein, 1983; Kitcher & Salmon, 1989; Nagel, 1979; Salmon, 1978, 1989).

Scientific explanations for natural phenomena often involve unseen entities such as atoms or forces, underlying processes such as genetic drift or oxidation, statistical or probabilistic patterns, or broad scientific theories to account for natural phenomena (Friedman, 1974; Kitcher, 1989, 1997; Salmon, 1978, 1989). For example, a description of condensation appearing on the outside of a cold glass of water differs from an explanation for condensation in that the description emphasizes observable features of the phenomenon such as the cooler temperature of the water in the glass and the presence of droplets on the outside of the glass. In contrast, an explanation for condensation emphasizes unobservable processes such as molecular motion and energy, employs key scientific ideas and theories, and often seeks underlying causes for a commonly observed phenomenon.

Both scientists and science students benefit from seeking scientific explanations. Salmon (1978) highlights the advantages for scientific thought of making a move from descriptive to explanatory accounts in an address to the American Philosophical Association:

> It provides knowledge of the mechanisms of production and propagation of structure in the world. That goes some distance beyond mere recognition of regularities, and of the possibility of subsuming particular phenomena thereunder. It is my view that knowledge of the mechanisms of production and propagation of structure in the world yields scientific understanding, and that this is what we seek when we pose explanation-seeking why questions. The answers are well worth having. That is why we ask, not only “What?” but “Why?” (p. 701)

For science teachers working with middle school and high school students, a focus on scientific explanations affords an opportunity to teach for understanding, but this kind of focus is challenging for the majority of science teachers (Driver et al., 1994; Gamoran et al., 2003; Treagust, Chittleborough, & Mamiala, 2003). We have found that familiarity with philosophical models for scientific explanation helps science teachers develop deeper understanding of science content informing their decision making about what to teach and how to teach in science classes (Thompson, Braaten, & Windschitl, 2009b; Thompson, Windschitl, & Braaten, 2008). From a philosophical perspective, there are many ways of conceptualizing scientific explanations, all of which can be relevant for research and practice in science education. After a brief review of each of the major models of scientific explanation from philosophy of science, we will describe how each can provide important insights for science educators.

The “Covering Law” Model of Scientific Explanation

**Covering Law Explanations in Philosophy.** The original model for scientific explanation was the deductive–nomological (D–N) or “Covering Law” model of explanation put forth by
Hempel and Oppenheim (1948). These philosophers saw science as a discipline illuminating regularities of the natural world that could then be expressed in statements as “natural laws.” When seeking an explanation for an event in the natural world, scientists look to natural laws that can account for particular events as logical, expected outcomes based on well-established patterns. Once a natural law is expressed in a field of science, it can be used to explain events “covered” by that law. For example, students in a chemistry class frequently use laws such as Boyle’s law to explain particular relationships between the volume of a gas and the pressure necessary to maintain that volume. Laws often provide mathematical means of representing persistent patterns observed in nature, and students use these laws to perform calculations as part of their explanation showing how specific observable events are logical outcomes of well-known patterns.

The Covering Law model for scientific explanations has been subjected to a number of critiques by philosophers who find fault with the symmetry of the explanations, with the inability to account for unlikely events, and with difficulty explaining events that are not covered by a natural law. Covering Law explanations are often confusing because causes and effects of phenomena can seem interchangeable—a problem often referred to as symmetry within the explanation. Salmon (1989) provides the example of observing a rapid drop in the reading on a barometer and then inferring that a storm is approaching because whenever the barometric pressure drops a storm follows. It does not make sense to say that the change in the reading on the barometer explains the occurrence of the storm, but the statement fits the Covering Law model of explanation because an event is explained as the logical outcome of an observed regularity. Salmon points out that our intuition in this case is to seek a common cause for both the storm and the barometer reading to provide clear, asymmetrical explanations for the developing storm and the falling barometer reading.

Philosophers also find fault with the Covering Law model because it does not accommodate explanations of unlikely events or of events that are not governed by natural laws. Cartwright (1997) argues that reliance on laws for constructing scientific explanations is problematic primarily because very few “covering laws” exist, especially outside of physics. Instead of relying on laws, many of the scientific explanations that are generally accepted by scientists employ generalizations that resemble laws. Cartwright maintains that this use of “false laws” should not detract from the quality of the scientific explanation. Instead, these statements tend to “express our explanatory commitments” helping to define what does and does not count as a possible explanation (p. 163). For example, it is not uncommon for teachers and students in physical science classrooms to explain the solubility of polar solutes in polar solvents and nonpolar solutes in nonpolar solvents by appealing to a “law-like” statement that “like dissolves like.” While this “law-like” statement may be helpful for reminding students about some rules of thumb in chemistry, it does not fully explain exactly what is happening at an atomic or molecular level when certain solutes dissolve in certain solvents. However, for science educators, the “like dissolves like” rule may signal certain explanatory commitments that are worth pursuing in greater depth such as pressing students to further unpack the important role of polarity in solubility. Because of the numerous critiques of the Covering Law model of explanation, philosophers of science, including Hempel himself, have considered additional models for scientific explanations that might satisfy some of these objections and provide more satisfactory accounts for natural phenomena (see Table 1 for a summary).

Covering Law Explanations in Science Classrooms. Critiques from Salmon and Cartwright are important not only from a philosophical standpoint but also from a pedagogical standpoint because they hint at the shortcomings of “Covering Law” explanations in supporting student reasoning. Chemistry students could rely on the gas laws to “explain”
### TABLE 1
Five Philosophical Models of Scientific Explanation Relevant for Science Education

<table>
<thead>
<tr>
<th>Models of Explanation</th>
<th>Attributes of an Explanation</th>
<th>Relevance to Science Education</th>
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<tbody>
<tr>
<td><strong>Covering Law</strong></td>
<td>• Deductive arguments</td>
<td>• STUDENTS: Students’ first</td>
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<td></td>
<td>explaining events as natural,</td>
<td>attempts at explanations often</td>
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<td></td>
<td>logical results of regularities</td>
<td>follow this form explaining a</td>
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<td></td>
<td>expressed by laws.</td>
<td>specific event by citing a law or</td>
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<td></td>
<td>• Merits depend on logical</td>
<td>using a law-like statement.</td>
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<td></td>
<td>coherence of the argument</td>
<td>• TEACHERS: Teachers can listen</td>
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<td></td>
<td>showing an event to be the</td>
<td>for—and then extend—students’</td>
</tr>
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<td></td>
<td>expected result of a natural</td>
<td>attempts at explanation.</td>
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<td></td>
<td>law (see Hempel &amp; Oppenheim,</td>
<td>• ISSUES: Fosters algorithmic</td>
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<td></td>
<td>1948).</td>
<td>reasoning but may not develop</td>
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<td></td>
<td></td>
<td>students’ conceptual reasoning</td>
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<td></td>
<td></td>
<td>or theory-building abilities.</td>
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<td>**Statistical-</td>
<td>• Induction from a trend or</td>
<td>• STUDENTS: Engages students in</td>
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<td>Probabilistic**</td>
<td>pattern in data may or may</td>
<td>important data analysis practices</td>
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<td></td>
<td>not seek underlying causes for</td>
<td>especially in fields relying on</td>
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<td></td>
<td>events.</td>
<td>large data sets like population</td>
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<td></td>
<td>• Merits of explanation depend</td>
<td>biology and earth science.</td>
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<td></td>
<td>on degree of coherence</td>
<td>• TEACHERS: Teachers can engage</td>
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<td></td>
<td>between explanation and data</td>
<td>students in data interpretation</td>
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<td></td>
<td>(see Hempel, 1965; Salmon,</td>
<td>and scaffold students’ attempts</td>
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<td></td>
<td>1989).</td>
<td>at making inferences from data.</td>
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<tr>
<td><strong>Causal</strong></td>
<td>• Induction from patterns in data,</td>
<td>• ISSUES: Focuses on data and</td>
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<td></td>
<td>but explicitly seek underlying</td>
<td>data representations but can</td>
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<td></td>
<td>causes for events.</td>
<td>divert attention away from</td>
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<td></td>
<td>• Merits depend on coherence</td>
<td>phenomena and mask causes of</td>
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<td></td>
<td>with data and on degree of</td>
<td>events.</td>
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<td></td>
<td>confidence in establishing</td>
<td>• STUDENTS: Capitalizes on</td>
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<td>causation (see Salmon 1978,</td>
<td>students’ curiosity and engages</td>
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<td>1989).</td>
<td>students in theorizing about</td>
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<td>unobservable causes for</td>
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<td></td>
<td>observable phenomena.</td>
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<td>• TEACHERS: Teachers can engage</td>
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<td>students in theorizing and</td>
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<td></td>
<td>model building.</td>
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<td></td>
<td></td>
<td>• ISSUES: Involves an inherent</td>
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<td>challenge of establishing</td>
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<td>causation. Tendency toward</td>
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<td>developing only simple, linear</td>
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<td>cause—effect relationships</td>
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<td>instead of causal webs and</td>
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<td>models.</td>
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(Continued)


The table continues with the following entries:

<table>
<thead>
<tr>
<th>Models of Explanation</th>
<th>Attributes of an Explanation</th>
<th>Relevance to Science Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pragmatic</td>
<td>Relies on shared agreement about the &quot;contrast class&quot; inherent in the why-question: Why is this (and not that) the case? Attributes negotiated and deemed acceptable by participants in conversation.</td>
<td>STUDENTS: Encourages explicit communication between teachers and students about locally constructed norms and meanings for explanations affording sense-making opportunities.</td>
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<td></td>
<td>Varied assumptions about contrast class may cause disagreement about what makes a satisfactory explanation (see van Fraassen, 1980).</td>
<td>TEACHERS: Teachers can listen to students’ attempts and better understand student thinking before posing follow-up questions.</td>
</tr>
<tr>
<td></td>
<td>STUDENTS: Encourages explicit communication between teachers and students about locally constructed norms and meanings for explanations affording sense-making opportunities.</td>
<td>ISSUES: Is not a stand-alone model of explanation but offers an important analytical tool for teachers listening to students.</td>
</tr>
<tr>
<td></td>
<td>STUDENTS: Encourages students to focus on &quot;big ideas&quot; in science by emphasizing major scientific theories and explanations.</td>
<td>TEACHERS: Affords a way of evaluating explanatory power of student-generated scientific explanations.</td>
</tr>
<tr>
<td></td>
<td>STUDENTS: Encourages students to focus on &quot;big ideas&quot; in science by emphasizing major scientific theories and explanations.</td>
<td>ISSUES: Not helpful for creating explanations of single events—more useful in concert with other models.</td>
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</tbody>
</table>

many aspects of the behavior of gases without reasoning through underlying theoretical ideas about the particulate nature of matter or the ability of tiny particles to exert forces during collisions. Driver Leach, Millar, and Scott (1996) argue that “Covering Law” explanations foster algorithmic reasoning, but they do not foster sophisticated reasoning or deep conceptual understanding because students do not need to engage in reasoning beyond the use of laws.

Driver et al. (1996) point out that many everyday ways of explaining events take the form of “Covering Laws.” For example, the authors envision a child asking a parent why the frying pan has a plastic handle, rather than a metal one. The parent responds that plastic does not conduct heat, but metal does; therefore, plastic handles do not get hot when the pan is on the stove. The parent’s explanation involves a statement asserted as a fact in a “law-like” form similar to those suggested by Cartwright. There are certainly more details that could be included in the explanation, but the parent’s response essentially takes the form of a Covering Law explanation with “plastic does not conduct heat” being used as a sort of law. Driver and her colleagues encourage teachers and students to explore additional models of explanation to foster deeper understanding in science. However, the Covering Law model of scientific explanation does satisfy some of our intuitions...
about explanations by using logical argument construction based on persistent patterns observed in the natural world. In science classrooms, students often begin their attempts at providing scientific explanations by creating statements that resemble “Covering Law” explanations.

In our secondary science classrooms, it is common to hear students making statements appealing to a law-like regularity as a way of accounting for something observed in nature. For example, we recently sat down with two students who were just beginning to examine phase changes in water. They had recently read about the behavior of molecules as ice melts and as water is boiled. The students were looking closely at a beaker of water sitting on a hot plate; water vapor was just beginning to rise from the surface of the water when we asked, “So why do you think that water vapor is starting to rise from the beaker of water?” One student replied matter of factly, “Because it’s on the hot plate heating up, and that’s what happens right before it boils.” When we think about this student’s attempt at explaining vaporization, we can see that she is using her knowledge of prior patterns when she remarks “because that’s what happens when…” and she is explaining the vaporization using this pattern as a kind of “law.”

By recognizing the law-like quality of students’ initial attempts at explanation, we are given a starting place for pressing students to move beyond chalking up a phenomenon to a law or a generalization when it is often possible for them to dig deeper and think in terms of underlying causes or in terms of powerful theories. Rather than simply criticizing students for failing to fully explain a phenomenon, we can recognize their initial attempts at explanation as being similar to Covering Law explanations and then give explicit types of feedback. We can communicate with students about how their initial attempt at explanation lacks certain attributes such as a causal relationship or an overarching scientific theory in an effort to press them to construct deeper scientific explanations. Alternatively, we may choose to accept students’ Covering Law explanations in certain circumstances, such as during a physics unit focused on mechanics, where law-like statements are the disciplinary norm for sufficient scientific explanations.

**Statistical Model of Scientific Explanation**

**Statistical/Probabilistic Explanations in Philosophy.** A second type of scientific explanation, the statistical or probabilistic model, is sometimes seen as a subset of other models for explanation. Some philosophers of science argue that explanations employing statistical and probabilistic reasoning are among the most important and complex in science (Hempel, 1965; Salmon, 1989). Phenomena such as the decay rate of radioactive isotopes, the likelihood of inheriting a particular gene combination, or the chance of sea levels rising in response to global warming are often understood by using mathematical reasoning rather than appealing to laws or generalizations. Mathematical constructs like rates and probabilities may not follow universal generalizations of the sort initially imagined by Hempel and Oppenheim (1948). In some cases, such as phenomena examined in theoretical physics, the phenomena can appear random rather than regular. Statistical models of scientific explanation are used in these cases to provide an account for phenomena that are not “covered” by a law. For example, when it is observed that many residents of a small town are developing an unlikely form of cancer, we cannot explain the higher incidence of cancer using a law-like statement because the appearance of the cancer was unexpected. Instead, we seek other explanations for the increased rate of cancer, such as exposure to a particular carcinogen present in the area. By connecting an increased incidence of cancer to an increased exposure to a carcinogen, we create a statistical explanation built from a correlation in data. However, there is also an underlying biochemical process at work.
when a carcinogen causes cancer. Examining data to arrive at a statistical or probabilistic explanation only partially assists us in explaining how certain phenomena work. This small, but consequential, detail reveals a concern about relying on statistical models of scientific explanation.

Salmon (1989) raised objections about statistical scientific explanations because he was concerned that emphases on statistics might gloss over the actual underlying explanation for events. He illustrated his objections with the classic example where a doctor notices that a patient recovered from a cold after a week of taking vitamin C supplements. The doctor then conducts a study and finds that all patients recovered from their colds after a week of vitamin C treatments, which seems to imply that vitamin C is the cure for the common cold. Unfortunately, by focusing on data about vitamin C treatments we have overlooked the important detail that patients will usually recover from colds within a week regardless of the vitamin C because colds are caused by self-limiting viruses that healthy immune systems can usually handle. Salmon argues that in this case, probabilistic reasoning might actually impede efforts to understand deeper explanations, but he allows that there are many areas of science where statistical and probabilistic scientific explanations are critical for understanding phenomena.

**Statistical/Probabilistic Explanations in Science Classrooms.** In school science contexts where students are examining phenomena by using large data sets, statistical scientific explanations may play an important role, a point emphasized by Duschl (1990, 2000). For example, in a science class focusing on population genetics, probabilistic data can be used to make sense of variations in gene pools across time and geography, as well as predict future trends. From our own recent study of novice teachers’ development of practice (Thompson et al., 2009a 2010; Windschitl, Thompson, & Braaten, 2008a, 2011) one teacher named Sarah pursued such an explanation during a genetics unit in her high school biology class. Students were engaged in examining two data sets: (1) a map of Africa showing allele frequencies of sickle cell anemia and (2) a second map of Africa showing epidemiology data about malaria. Sarah engaged students in an investigation into the relationship between these two diseases. At the end of the unit of study, students were asked to use probabilistic reasoning with the data sets and to use their understanding of inheritance patterns and evolutionary theory to explain the continued existence of a harmful gene in a population. Sarah’s example illustrates that in many cases where statistical explanations might be warranted, teachers and students could also be focusing on the complex causes for events, the mediating factors that complicate natural systems, and the central theories in science that provide the underpinnings for our current understanding of phenomena. This strongly suggests that teachers will need to be knowledgeable and flexible in their ability to juggle multiple models of scientific explanation simultaneously requiring a special kind of pedagogical content knowledge that Treagust and Harrison (2000) term “explanatory flexibility” (p. 1161).

**Causal Model of Scientific Explanation**

**Causal Explanations in Philosophy.** Both the Covering Law model of scientific explanation and statistical models of scientific explanation hint at, but do not fully satisfy, a strong intuition about scientific explanation—our desire to understand the causes for events in nature. Salmon (1978) suggests that scientific explanations seem most compelling when they offer understanding of the causes underlying natural phenomena. While the other models of scientific explanation may include causal relationships, they do not explicitly emphasize
causation as a key attribute of explanatory power. Salmon argues that explanatory power is enhanced when causal scientific explanations involve ideas from scientific theories to account for phenomena, such as using gravitational theory to explain the regularity of tides or using kinetic molecular theory to explain the behavior of gases. Both tides and behaviors of gases can be readily described by laws using the Covering Law model of explanation, but the desire for a causal account is better satisfied when theories and underlying mechanisms are included in the explanation. The causal model of scientific explanation has advantages in that it often resolves some of the puzzles of the Covering Law model, including the symmetry problem and the problem with explaining unexpected events; however, causal scientific explanations rely on our ability to establish causation, which is a puzzle that has plagued philosophers for well over a century and continues to stir debate (Salmon, 1989). The principal challenge of a causal model of scientific explanation lies in locating and substantiating underlying causes for phenomena, which requires a degree of inference to establish connections between causes and effects. Despite these difficulties, the causal model of scientific explanation remains the preferred model for many disciplines of science.

**Causal Explanations in Science Classrooms.** Many of the phenomena examined in school science classes have well-established causal explanations that form the conceptual bases of many disciplines in science. In microbiology, for example, scientists are almost always seeking causes for phenomena such as the infectious agent responsible for disease symptoms, the epidemiology of a particular outbreak of a disease, or the chemical profile of soil samples during bioremediation. Without causal scientific explanations, neither the student nor the microbiologist would really understand phenomena such as disease, epidemics, or bioremediation. However, just as philosophers of science find causation to be conceptually and philosophically challenging, science teachers face challenges when pressing for causal explanations in science classes.

Perkins and Grotzer (2005) note that both teachers and students are able to propose simple, linear cause–effect models to explain phenomena, but they often have a difficult time proposing more complex storylines that include interrelated causes and mediating factors that more accurately represent the kinds of explanatory models employed in biological sciences. However, when students are able to craft complex, causal explanations for biological phenomena, their understanding of the phenomenon and of the underlying biological ideas are enhanced (Grotzer & Basca, 2003). In our research, we have found that by providing novice science teachers with some background knowledge about causal scientific explanations and then pressing them to wrestle with these explanations during their science classes, we can help teachers identify the major scientific ideas worthy of in-depth inquiry for their students (Thompson et al., 2009a, 2010; Windschitl et al., 2008a).

One of the teachers in our study, Simon, often considers the full causal explanation for phenomena when he plans units of instruction designed to help Grade 9 students understand major science ideas deeply (Thompson et al., 2010; Windschitl et al., 2011). For example, during Simon’s second year of teaching he decided to modify the “Sound and Waves” unit of instruction. The science textbook suggested covering every kind of wave and focusing students on calculating wavelengths, frequencies, and amplitudes, but Simon felt that none of these isolated ideas helped students explain the differences in sounds that they could hear and feel when attending concerts. As a result, he engaged students in investigations into the movement of sound energy through the medium of air and examinations of the intensity and pitch of sounds using music software on their computers. Students developed
rich explanatory models to account for the sounds that they heard coming from musical instruments and were able to expand those models to think about other phenomena such as echoes and movement of sound through another medium such as water. A focus on causal explanations has helped Simon, and many of our other beginning teachers, make an important move toward organizing units of instruction around “Big Ideas” in science and focusing students’ science investigations on explanation and theory-building in addition to observation and description (Windschitl et al., 2010).

Pragmatics of Explanation

Pragmatics of Explanation in Philosophy. Philosophers taking a pragmatic view of explanation do not suggest a specific model for scientific explanation. For those taking a pragmatic view of explanation, the context surrounding the request for an explanation determines whether or not a response “counts” as a satisfactory explanation. In other words, the adequacy of an explanation stems not just from features of the explanation, but from the question initiating the explanation as well as the context surrounding the question (Achinstein, 1983). By looking at the whole context in which an explanation is constructed, we can understand how groups of people construct explanations together in social settings similar to those examined in studies of practicing scientists (Knorr-Cetina, 1999; Latour & Woolgar, 1986; Traweek, 1988).

This fourth view of explanation is well articulated by Bas Van Fraassen (1980), who critiques other attempts at developing a singular, unified theory for scientific explanation because these attempts fail to place explanations in context. He argues that when context is taken into account, the standards for judging the merits of explanations are not solely about the alignment between theory and facts but are also negotiated between participants who are constructing the explanation in a particular context. For example, multiple people could discuss a recent car accident at a three-way intersection seeking an explanation for the accident. Owners of businesses on the corners of the intersection might explain the crash by citing the continued hazards posed by the awkward intersection design. The city manager might explain the accident by citing the need for a traffic signal to regulate drivers at the busy intersection. The driver of one of the cars might explain the accident by noting his difficulty with blind spots in his car. Each explanation, for philosophers who take the pragmatic view of explanation, is acceptable so long as the local participants in the conversation determine that the explanation satisfies their request for an explanation.

Van Fraassen (1980) argues that the key factors in determining the adequacy of explanations are the “contrast class” and the “relevance relations” that are emphasized by participants in a discussion. The local business owners emphasized that this particular accident is simply the logical outcome of the many near-accidents that happen at the awkward corner. The contrast class, in the case of these local residents, is the set of near-accidents and the detail that is most relevant is the unusual convergence of three streets at the intersection. However important these details are to the group of local business owners, they are not important for the driver who is more focused on the problems caused by blind spots in his car, which could have caused him to crash at this or any other intersection. Differences in contrast class and relevance relations cause people to propose different explanations for the same event that are equally acceptable and valid, but that can sound completely irrelevant to different participants in a conversation.

Pragmatics of Explanation in Science Classrooms. Understanding Van Fraassen’s arguments and the pragmatics of explanation has helped our support of science teachers and
students in important ways. By examining the multiple interpretations of both the request for explanation and the responses provided by our secondary science students, we can see the importance of developing shared understanding about scientific explanations. For example, in a sixth-grade physical science class, the first author worked with students to explain the movement of water through the hydrologic cycle. During a class period when students were drawing upon recent experiments with phase change and a reading about the molecular motion and energy transfer, the first author asked one student, “Why do water molecules move from lakes, into the atmosphere, and then into clouds?” The student responded that water moves this way because animals and plants need water to survive. Although the teacher had frequently emphasized attributes of causal explanation and provided scaffolding prompting students to include ideas about unobservable, underlying mechanisms, the “why” question itself lacked specificity and failed to communicate the kinds of ideas that the teacher “counts” in an explanation. It makes sense, then, that the student’s response does not include ideas about molecules, energy, or phase change and focuses instead on how living things require water. Thinking about explanation from a pragmatic perspective has helped us realize how important it is to reframe our questions to clarify the contrast class and make explicit the kinds of details relevant for a good explanation. In many cases, including this one, a follow-up conversation was necessary to co-construct the kinds of ideas that “count” in a good explanation about phase change. Developing scientific explanations as well as negotiating what “counts” as a good scientific explanation within the context of a science classroom has afforded an opportunity for shared knowledge construction that is not otherwise present.

Explanatory Unification View of Scientific Explanation

Explanatory Unification in Philosophy. A final model for scientific explanation is the explanatory unification view advanced first by Friedman (1974) and later by Kitcher (1989, 1997). This perspective builds upon prior conceptualizations of scientific explanation and contends that explanatory power is increased when explanations can unify seemingly disconnected phenomena into a coherent relationship, providing “global rather than local” understanding of phenomena (Friedman, 1974, p. 18). Powerful theories in science, such as the kinetic molecular theory, derive their explanatory power from their ability to provide explanations for different phenomena across many contexts. For example, instead of relying on one explanation to account for the way that heated air inflates a hot air balloon and then employing a different explanation to account for the condensation of water vapor on the outside of a cold glass, we can use the kinetic molecular theory to account for both of these seemingly unrelated phenomena. Instead of providing an entirely new model for scientific explanation, explanatory unification provides a way of evaluating the explanatory power of theories and conceptualizing how powerful scientific explanations deepen scientific understanding in ways that descriptions and descriptive laws cannot.

Friedman (1974) argues that powerful scientific explanations should promote deeper understanding of the natural world. He maintains that if scientific explanations are simply logical arguments about the natural world, as suggested by proponents of the Covering Law model, then providing a scientific explanation does nothing more than replace “one brute fact with another” (p. 14). Instead, Friedman suggests that powerful scientific theories, like the kinetic molecular theory, afford the ability to apply explanations for phenomena across a range of observations and help us to unify phenomena and their explanations. It is this unification, according to Friedman, that fosters understanding because “a world
with fewer independent phenomena is, other things equal, more comprehensible than one with more” (p. 15). The link between explanatory unification and the ability to better understand the natural world suggests an important role for scientific explanation in science education.

**Explanatory Unification in Science Classrooms.** The explanatory unification view of scientific explanation is important for science education for three reasons: (1) the emphasis is on sense making and understanding, (2) the focus is on big science ideas, and (3) there are clear ways to evaluate explanatory power. School science is often described as covering a range of topics that are a “mile wide and an inch deep” (Duschl & Grandy, 2008; NRC, 2007). The explanatory unification view demands that scientific explanations focus on overarching scientific theories that apply globally to phenomena not just locally. This view of scientific explanation offers a way for teachers to begin to pare down sprawling science curricula and focus intentionally on the most important ideas in each scientific field. The explanatory unification view of scientific explanations offers a means of evaluating the explanatory power of ideas in science—a valued theory-building practice emphasized in many science education reform documents (AAAS, 1993; NRC, 1996, 2007). Kitcher (1997) proposes the notion of the “explanatory store,” a set of explanations that already exist and are commonly held in scientific thought (p. 170). He suggests that newly constructed scientific explanations often draw from or are judged against ideas in this store. The notion of the “explanatory store” could further assist teachers in deepening the curricula to include the most central ideas in science and would offer a way of guiding students to evaluate explanatory power.

**Summary of Models of Explanation**

These five major models of scientific explanation from the philosophy of science are all relevant for science educators, not because of some priority given by philosophers, but because each is a legitimate practice of scientists and children attempting to craft explanations. Conceptual clarity about scientific explanations helps science educators envision what “counts” as a big idea in science lessons and units of instruction. A framework informed by philosophy of science also enables science educators to make sense of the partial attempts at explanation provided by students, which, in turn, allows teachers to make further decisions about how to proceed with instruction.

Most science educators in the United States, however, have not been immersed in philosophy of science ideas. Instead, many science educators look to literature in science education for guidance about what to teach and how to teach. The science education reform literature from the past two decades provides normative visions for what science education should be, whereas the literature from research in science classrooms illuminates how specific pedagogical practices, tools, and curricular innovations impact students’ learning experiences. We now turn to these two bodies of literature to see how the field of science education characterizes scientific explanations, how science educators are guided to recognize the power of certain kinds of explanations, and how science educators are helped to

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1 Salmon (1978) cautions that the concept of “understanding” belongs more to the domain of psychology than to philosophy, a distinction also offered by Hempel and acknowledged by Friedman, but Salmon concedes that powerful scientific explanations do satisfy many of our intuitions about understanding the natural world.
analyze and evaluate the merits of alternate explanations—in particular those provided by their students.

CONCEPTUALIZATIONS OF SCIENTIFIC EXPLANATION IN SCIENCE EDUCATION

Despite a strong emphasis on the role of scientific explanation in education, there is a lack of clarity about the concept of scientific explanation within the science education literature. Because it is the science education literature—not the philosophy of science literature—that ultimately informs science educators, conceptual clarity is essential for guiding instructional practice. In particular, the science education community needs more conversations about three overarching questions: (1) What constitutes a “good” scientific explanation in a science classroom?, (2) What makes an explanation explanatory rather than descriptive?, and (3) How might we evaluate the merits of alternate explanations offered by students in classrooms? Using philosophy of science as a lens, we examined recent research and reform efforts focused on developing scientific explanations in classrooms to better understand how the science education community conceptualizes scientific explanation.

Scientific Explanations in Science Education Research

Researchers in science education have conducted numerous studies designed to engage teachers and students in constructing, analyzing, and evaluating scientific explanations. However, many of these intervention studies do not specify their conceptualizations of scientific explanations in ways that can provide further guidance for other researchers and science education practitioners. Some studies present the construction of a scientific explanation as straightforward and unproblematic, whereas others focus on only one aspect of explanation. In some cases, scientific explanation is combined with argumentation. In the following sections, we describe the ways in which explanation is portrayed in science education research (see Table 2). Although the nature of explanation is typically consistent within various programs of research, it differs significantly across the field resulting in conceptual ambiguity.

*Explanation as Explication.* In the science education literature, it is common to see “explanation” used in the sense of providing clarification for the meaning of a term or explication of reasoning about a problem. In science classrooms, students are frequently asked to “explain their reasoning” while solving a problem, to “explain the meaning” of a technical term, or to “explain the results” of an experiment. Providing an explanation—or an *explication*—is in many ways an authentic communicative practice in the daily work of scientists who clarify ideas and findings to various audiences (Knorr-Cetina, 1999; Latour & Woolgar, 1986; Traweek, 1988). While it is important to engage in this kind of clarification to communicate, the practice of constructing scientific explanations that account for natural phenomena involves more than explications of meaning.

Ogborn, Kress, Martins, and McGillicuddy (1996) provide a thorough analysis of the ways that teachers and students engage in explication in the science classroom. Teachers or students might, for example, help another student to understand the meaning of unfamiliar vocabulary by explaining the term in a different way. The authors also point to
### TABLE 2
Common Uses of “Explanation” in Science Education

<table>
<thead>
<tr>
<th>Uses of “Explanation” in Science Education</th>
<th>Attributes of This Kind of Explanation</th>
<th>Examples in Science Classrooms</th>
<th>Ways This Use of “Explanation” Can be Problematic</th>
</tr>
</thead>
</table>
| **Explanation as expliciation**          | ● Definitions of terminology requested by teacher or students, prompted by instructional materials.  
● Metacognition about reasoning/problem-solving strategies requested by teacher or students, prompted by instructional materials. | In classroom discourse:  
● Can you explain what you mean when you say that the sugar “dissolved”?  
● Can you explain how you figured out the amount of force needed to lift that load with the pulley system? | ● The object of the explanation—what is being explained—is unclear.  
Explications are focused on terminology, meaning, and reasoning while scientific explanations are focused on natural phenomena.  
● Teachers and students engage in explication frequently, and may think that they are working on scientific explanations when they are not. |
| **Explanation as simple causation**       | ● Emphasis on cause-effect relationships accounting for an observable event. | In classroom discourse:  
● What’s making the sugar dissolve so fast?  
● Why does the cart roll faster on the smooth ramp than on the carpeted ramp? | ● Oversimplifies the nature of causation into simple cause-effect relationships instead of complex webs of causation.  
● Implies that causal explanation is the single, accepted model of scientific explanation when there are actually many acceptable models for scientific explanations. |

(Continued)
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</tr>
</thead>
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| **Explanation as justification**          | • Emphasis is on argument construction—often taking the form of “claim-evidence-reasoning.”  
• Requests for “explanations” are requests for evidence and reasons for belief in a claim. | In instructional materials:  
• What effect does “capturing” a particular color dot have on the numbers of that color in the following generations?  
• What effect did the salt have on the boiling point of water? | • Emphasis on scaffolding students’ use of evidence to justify claims overlooks possible explanatory power of claims.  
• Claims prompted by these efforts are often assertions or descriptions rather than explanatory (how/why) claims.  
• Successful scaffolding for explanatory claims is downplayed and therefore invisible to other science educators. |
|                                          | In classroom discourse:  
• How do you know that this gas is carbon dioxide?  
• What makes you so sure that no other forces are acting on the cart? | In instructional materials:  
• What evidence was there that chemical reactions were occurring?  
• Work with the members of your team to determine which explanation best accounts for the data presented. |                                                |
the importance of helping students “see” theoretical entities and actions in the same way that scientists see them through the use of explication. In a chemistry or physics class, for example, teachers rely on explication to help students envision subatomic particles, waves, energy, or forces acting across multiple unobservable contexts. In this sense, Treagust and Harrison (2000) bridge the practices of creating scientific explanations and providing explications with their concept of a science teaching explanation. Science teachers often use a variety of discursive strategies including metaphors, analogies, and vignettes to communicate well-established scientific explanations to students. Treagust and Harrison recommend that teachers become well versed in a number of “explanatory frameworks” to provide better science teaching explanations in classrooms (p. 1158). These episodes of clarification are not in themselves examples of scientific explanations, but they may be integral to understanding the discourse moves required in classrooms where teachers and students are working to understand scientific explanations. Ogborn et al. and Treagust and Harrison are focusing primarily on instances when teachers explicate an idea to their students; however, it is also important to consider how students themselves might talk through their own ideas about science.

For students to make sense of science ideas like particles or energy, and engage in construction of explanations, we must create opportunities for students to talk about science—to explicate aloud (Herrenkohl, 2006; Lemke, 1990; Mortimer & Scott, 2003). In such cases, explication may be a necessary step when helping students construct scientific explanations for phenomena, but it is not synonymous with scientific explanation. Much of the focus on scientific explanation in schools tends to portray “explanations” as knowledge produced by scientists and then explicated to students by teachers through skillful use of representations, stories, discussions, and analogies (Millar & Osborne, 1998; Treagust et al., 2003). We would like to extend Treagust and Harrison’s (2000) notion of building explanatory frameworks with teachers to include building explanatory frameworks with students as well. By working together to establish what “counts” as a good explanation depending on contextual factors such as disciplinary norms and science ideas available to students at certain times of year or in certain courses, teachers and students could develop shared understanding and further the knowledge construction in their classrooms.

The term “explanation” is also used to connote the communication of reasoning in an effort to make thinking visible or audible in science classrooms. Coleman (1998) examined students’ explanations in science as part of a study on student learning in problem-based science classes; however, the explanations that were examined were not scientific explanations. Rather, students were prompted to explain their reasons for thinking that a particular answer to a question was justified, to defend why they believed their answers to be correct, or to reflect on changes in their thinking over time. During conversations with students, for example, Coleman describes how a prompt such as “Ok, explain why you believe that your answer is correct or wrong?” pushes students to communicate their reasoning (p. 406). Similarly, a prompt such as “Can you compare how you used to think about this with how you think about it now?” helps to further conversations with students (p. 407). Berthold, Eysink, and Renkl (2009) and Wittwer and Renkl (2008) found that having students construct these kinds of explanations of reasoning on their own or with a peer offers an opportunity for sense making that does not seem to happen when students simply listen to an instructional explanation from a teacher or read one in a text. Creating opportunities for students to verbalize their thinking with peers and with teachers is critical to helping students make sense of science ideas and may be key components to helping students engage in productive classroom discourse, but this type of classroom task does not appear to call for scientific explanation itself.
The confusion created by the use of the term “explanation” as a synonym for clarification or for communication of reasoning is not merely one of semantics. The problem is that the object of the intellectual work—what is being explained—is different for each sort of explanation. Scientific explanations seek to explain events in the natural world. However, when teachers press students to explicate the meaning of words or to communicate their thinking about a problem or their procedures for arriving at solutions to problems, the object of the “explanation” is no longer natural phenomena. In addition, because teachers request “explanations” often in classrooms, they may believe that they are pressing for scientific explanations when, in fact, there may be nothing explanatory about the intellectual work at all. To provide the conceptual clarity necessary for supporting science educators, it is important that we tease apart the important everyday discursive activities of clarifying terms and communicating reasoning about ideas from the specific science discourse practice of crafting scientific explanations.

**Explanation as Causation.** Some scholars in science education take a perspective that to explain a natural phenomenon we must establish a causal account using underlying mechanistic properties of the natural world to explain observable phenomena (cf Windschitl, 2008; Hammer, Russ, Mikeska, & Scherr, 2008; Russ, Scherr, Hammer, & Mikeska, 2008). Hammer et al. make the strong claim that causal, mechanistic accounts of phenomena are the principle kinds of explanations in science. For many disciplines of science, developing causal explanations are indeed central practices for making sense of phenomena, and many of the big ideas addressed in school science have well-known causal explanations. There are certainly branches of science in which causal explanations are not the coin of the realm. Fields such as population genetics and quantum physics utilize statistical and probabilistic reasoning to make sense of phenomena for which there may not be any underlying cause or regular mechanism. Other fields, such as classical physics, employ laws—statements of observed regularities—rather than underlying causes to account for the operation of simple machines or to describe the motion of certain objects. By pressing for causal explanations exclusively, science educators may be misrepresenting the kinds of scientific explanations actually employed in the sciences.

Looking to the disciplinary norms of practicing scientists can illuminate both the fine-grained differences between explanation practices in subdisciplines of science and point to the explanatory practices that science fields have in common. When researchers in science education make clear these disciplinary norms, it helps science educators better understand how to create such science learning environments. For example, Grotzer and her colleagues (see Grotzer, 2003; Grotzer & Basca, 2003; Perkins & Grotzer, 2005) study classrooms emphasizing complex causal models for biological phenomena. The researchers noticed that students and teachers tended to explain ecological relationships with simple, linear cause–effect explanations. However, they wanted students’ explanations to more closely resemble those used by ecologists—nuanced and complex webs of explanations employing a combination of causal and statistical/probabilistic explanations. As a result, Grotzer and her colleagues worked to press teachers and students to combine causal and statistical reasoning.

Palincsar, Anderson, and David (1993) also appealed to the disciplinary practice of scientists when they chose to emphasize causal explanations employing unobservable or theoretical entities to account for change of state, solubility, and other physical and chemical phenomena common to school science. Like Hammer and his colleagues (2008), the intervention of Palincsar et al. focused on crafting science instruction pressing
students to create a particular kind of scientific explanation—a causal explanation using unobservable underlying mechanisms—but Palincsar et al. provided insight into their way of conceptualizing scientific explanations, thus giving guidance to other science educators.

When scholars in science education communicate the rationale behind a choice to focus on a specific kind of scientific explanation, their work can provide both a rich, discipline-specific conceptualization of scientific explanation and guidance for pedagogical decision-making useful to other science educators. However, it is important to consider how using multiple models of scientific explanation together might foster authentic epistemic practices and complex reasoning in ways that total allegiance to a singular model of scientific explanation cannot. Being able to provide a causal account of the natural world satisfies an intuition about scientific explanation that has been repeatedly emphasized by philosophers of science; however, our point here is that establishing some clarity of meaning for explanation does not necessarily require allegiance to a singular form of explanation. Instead, we are advocating an explicit conversation within the field about what makes explanations explanatory, rather than descriptive, and about how teachers and students can engage in generating, rather than only justifying, explanations.

Explanation as Justification. Scientific explanation and argumentation are key practices in science with a long intellectual history of analysis by philosophers of science and a recent surge in analysis by researchers in science education (Berland & Reiser, 2009; Bricker & Bell, 2008; NRC, 2007). Berland and Reiser point out that many science education researchers treat explanation and argumentation as a single practice because they are so interconnected epistemically in terms of using evidence and logic as part of a specialized rhetorical genre. But they also suggest that both teachers and students may benefit from educational supports that tease apart aspects of scientific explanation from argumentation. A number of studies in science education have sought ways of supporting teachers and students in constructing and defending scientific explanations—these interventions emphasize both argument construction and the development of powerful explanatory ideas; however, the reader must work to recognize the distinctions. When, for example, is one engaged in the work of argument construction, and when is one working to develop explanatory ideas? Osborne (2010) and Bell (2010) recently highlighted the challenge that this disentanglement presents for science educators who are trying to make an explicit choice to focus science learning on a few particular scientific practices—making a choice of practices often means that some worthwhile practices lose emphasis while others receive more explicit emphasis. Bell recommends that we take time to carefully consider a variety of scientific practices by examining students’ everyday practices, by examining scientific practice, and by exploring how certain practices offer opportunities for sense-making about science ideas.

Recently, a number of worthwhile interventions have addressed teachers’ and students’ work with scientific explanations and argumentation. While these interventions have made major strides toward supporting shifts in reform-oriented science teaching, they have tended to prioritize argumentation at the expense of explanation. McNeill and Krajcik (2008) along with other colleagues (McNeill, Lizotte, Krajcik, & Marx, 2006; Moje, Peek-Brown, Sutherland, Marx, & Krajcik, 2004) describe scientific explanation as synonymous with scientific argumentation. Curricular materials for this intervention define scientific explanations as statements consisting of “three components: claim, evidence, and reasoning” (McNeill, 2009; McNeill & Krajcik, 2008). McNeill et al. (2006) are careful to prompt readers that “explanations often refer to how or why something happens” (p. 155). This reference to “how or why” is subsequently lost within the intervention as it shifts emphasis toward supporting students’ argument construction. For example, students are prompted to “write
a sentence that states whether or not boiling is a chemical reaction” and later to “write a sentence that states whether the mass stayed the same or not” (p. 165). Students are then prompted to provide pieces of evidence to substantiate their claims and to write statements illustrating their reasoning about the evidence. Similarly, Songer, Kelcey, and Gotwals (2009) used the “claim, evidence, reasoning” format to scaffold sixth-graders’ attempts at explaining their responses to questions such as “Is this animal an insect?” (p. 615). These interventions provide much needed support for students’ attempts at justifying claims by using evidence, but the students’ claims are not explanatory. How can the field of science education capitalize on these worthwhile interventions scaffolding students’ argumentation practices while also helping students build strong explanatory claims? How can we help students engage in theorizing as well as justifying claims?

Sandoval and his colleagues (Sandoval, 2003; Sandoval & Millwood, 2005; Sandoval & Reiser, 2004) report findings from their studies of an intervention designed to help students construct evidence-based explanations of the biological diversity of finches on the Galapagos Islands employing a tool called ExplanationConstructor. Sandoval (2003) conceptualizes scientific explanations in this study as “plausible causal accounts” employing data such as finch population sizes and observations such as beak shape to explain finch diversity in a manner consistent with the theory of natural selection. Central to Sandoval’s framing of scientific explanation is the requirement of “causal coherence” meaning that students’ explanations should be internally consistent as well as consistent with generally accepted scientific principles and theories. To reach these educational goals, the software poses specific questions prompting students to think about causation and directs students’ attention toward salient data, observations, or aspects of scientific theories that are particularly relevant for the explanation of this phenomenon.

The researchers found that students were highly successful at constructing explanatory claims, but, because students struggled with providing evidence and reasoning to support those claims, the researchers’ focus remained fixed on aspects of argumentation that seemed most problematic for these students. Sandoval (2003) focused on students’ coordination of evidence with theory and downplayed students’ successful construction of solid explanatory claims, missing an opportunity, we believe, to highlight some very important scaffolding moves embedded in the tool.

Again, our critique here is not with the way that the researchers supported student thinking through rigorous and thoughtful intervention. Instead, our critique is that this research often features argument construction over scientific explanation as the focus of the scholarly work. Most science educators will not use robust teaching tools; instead, they will design instructional sequences using existing curricular materials and personal pedagogical decision making. To provide guidance to teachers hoping to replicate the successful scaffolding provided in the complex lesson design of ExplanationConstructor and other similar interventions, researchers should communicate their reasoning about scientific explanations and scaffolding used to encourage students to construct rich explanations for natural phenomena.

From these studies, it seems a conversation is needed in the field about how particular scaffolding supports for scientific explanations are useful for supporting the development of students’ explanatory ideas as well as argumentation practices. Currently, the curricula, prompts, and scaffolding in these studies direct students to use evidence and reasoning to support assertions resulting in well-articulated statements of justified belief, but not necessarily resulting in a scientific explanation consistent with models of explanation seen in philosophy of science. We note here that these critiques are not of the studies themselves—the studies are some of the most thoughtful and rigorous examples of research exploring
the boundaries of students’ epistemic practices. It is our hope, however, that attention and guidance for scientific argumentation and for scientific explanation can be developed by analyzing the features of both and identifying what features of thinking and discourse need to be scaffolded for each.

### Scientific Explanations in Science Education Reform Documents

Because education reform recommendations are widely used to craft instructional materials, shape instruction, and inform assessments, it is important to examine how these documents address scientific explanations. In the United States, two reform documents, the *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (NSES; NRC, 1996), underpin instructional materials often used in teachers’ science classrooms while a newer review of research, *Taking Science to School* (TSTS; NRC, 2007) sets the tone for current science education initiatives. We focus on U.S. reform efforts first because that is the context in which our preservice and in-service teachers work, but we also examine documents from the United Kingdom and European Union where scientific explanation plays a role in on-going science education reforms.

In the *Benchmarks*, scientific explanations are described as ideas crucial for making sense of scientific information and for determining the quality of scientific theories. However, the *Benchmarks* do not offer any clear conceptualizations of scientific explanation, often using the word “explanation” without providing any clarification of meaning. For example, the *Benchmarks* state that “scientific investigations usually involve the collection of relevant evidence, the use of logical reasoning, and the application of imagination in devising hypotheses and explanations to make sense of the collected evidence” (p. 12). In addition, the *Benchmarks* suggest that explanations play a critical role in the evaluation of scientific knowledge, stating that “theories are judged by the range of observations they explain, how well they explain observations, and how effective they are in predicting new findings” (AAAS, 1993, p. 13). While these assertions introduce the concept of explanatory power as a goal of theory building, they do not help to clarify what an explanation is nor do they offer any guidance about what gives some theories more explanatory power than others.

The *NSES* (NRC, 1996) suggest that science educators should focus on developing, revising, and communicating scientific explanations as part of an overall shift toward viewing “science as argument and explanation” (p. 113). The *NSES* envision a growth in the sophistication of students’ explanations as students advance through science courses, stating that “their scientific explanations should more frequently include a rich scientific knowledge base, evidence of logic, higher levels of analysis, greater tolerance of criticism and uncertainty, and a clearer demonstration of the relationship between logic, evidence, and current knowledge” (p. 117). In later sections of the *NSES*, the concept of scientific explanation is differentiated from descriptions by noting that students should be able to provide “causes for effects” and should be able to establish these cause-effect relationships “based on evidence and logical argument” (p. 145).

Like the *Benchmarks*, the *NSES* propose that students and teachers focus on evaluating the merits of scientific explanations as a way of understanding the growth of knowledge of science. The rationale here is that “the scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances” (p. 148). The criteria for evaluating alternative explanations, according to the *NSES*, include logical consistency, rules of evidence, revisability, testability, and coherence with historical and current ideas in science. While the *NSES* attempt a greater level of articulation than the *Benchmarks*, there is still no guidance for science educators,
curriculum developers, or other stakeholders regarding what gives a scientific explanation its explanatory power and little guidance for helping science educators craft learning environments that encourage construction and evaluation of scientific explanations.

The concept of scientific explanation plays a central role in *Taking Science to School: Learning and Teaching Science in Grades K-8* (NRC, 2007) and in its companion volume for classroom teachers, *Ready, Set, Science!* (NRC, 2008). According to TSTS, students should

- Know, use, and interpret scientific explanations of the natural world.
- Generate and evaluate scientific evidence and explanations.
- Understand the nature and development of scientific knowledge.
- Participate productively in scientific practices and discourses (p. 334)

*TSTS* draws upon developments in science studies to conceptualize science as a field that is “fundamentally about establishing lines of evidence and using the evidence to develop and refine explanations”; however, *TSTS* does not provide much guidance about the composition of scientific explanations. Scientific explanations in *TSTS* are typically conceptualized as “statistical models of natural phenomena . . . rooted in probabilistic reasoning” rather than cause–effect relationships (p. 18), but further guidance for science educators is not provided. The authors are critics of overly simplistic causal and mechanistic models for scientific explanation and are advocates for statistical and probabilistic models, but these models are not explicitly described. The volume critiques practices in science education that have conceptualized learning as the acquisition of facts or knowledge of specific cause–effect relationships and suggests shifting emphasis away from accumulation of facts toward a focus on scientific explanations for natural phenomena.

Scientific explanation plays an integral role in on-going science education reform efforts in Europe particularly in the United Kingdom. In *Beyond 2000: Science Education for the Future* (1998), the authors propose a turn toward science education that fosters understanding of the major “explanatory stories” of the natural sciences. This turn is in reaction to the observation that much of science in schools was being presented as a static body of knowledge irrelevant for students and for their futures as informed citizens.² Like the reform documents from the United States, *Beyond 2000* offers broad recommendations that science curricula should shift away from emphasis on describing and memorizing facts and toward explanations, discussions, problem solving, and writing to communicate ideas. *Beyond 2000* details some of the “explanatory stories” suggested as key components of science curricula and provides some guidance about the attributes of scientific explanations. For example, explanations often stretch beyond available data employing creativity when theorizing about how events happen because explanations are models of what people think is happening at a level that is not directly observable. *Beyond 2000* takes a position that the power of an explanation is increased when that explanation can predict outcomes, but concedes that sometimes there is not enough data to provide reliable predictions so in certain cases science is unable to offer more than a correlation.

Stemming from the recommendations in *Beyond 2000*, a new experimental course was developed for teachers and students as part of the science education reform efforts in the United Kingdom. *Breaking the Mould? Teaching Science for Public Understanding* (2002) offers an analysis of this reform effort and highlights some of the ways in which a turn toward scientific explanation as envisioned by broad reform documents can be challenging

² For a thoughtful critique of some of the framing of the *Beyond 2000* report, please see Donnelly (2005).
for teachers. Despite changes within the structure and content of the course, teachers’ classroom practice continued to rely heavily on presenting and explicating science ideas for students rather than engaging students in first-hand examination of data, discussion of ideas, or construction of scientific arguments and explanations. The authors attribute this shortcoming to three interrelated challenges: (1) underprepared and unsupported teachers who do not have pedagogical techniques for engaging in this kind of science instruction, (2) a lack of pedagogical tools within the new curriculum, and (3) a lack of supports to enable teachers to break away from the deeply ingrained practices of traditional science instruction. *Breaking the Mould* recommends that future efforts at science education reform should provide teachers with (1) support developing their own background knowledge about major explanatory science ideas across science subdisciplines and about the ways in which arguments and explanations are constructed in science, (2) support for providing scaffolding to foster student-to-student discourse about science ideas, and (3) support for scaffolding students written arguments and scientific explanations.

Recently, some of the concepts from *Beyond 2000* and *Breaking the Mould* resurfaced in recommendations for science education throughout Europe in *Science Education in Europe: Critical Reflections* (2008). Notable among the recommendations in this document is a push for science education across the European Union “to educate students both about the major explanations for the material world that science offers and about the way science works” (p. 15). Echoing recommendations of *Breaking the Mould*, this document stresses the need for a shift in science teaching practices from “deductive to inquiry-based methods” and help for teachers as they learn to engage in practices supporting student discussions and writing evidence-based explanations and arguments (p. 23).

Reform documents call for more emphasis on scientific explanation in science classrooms. They push educators to move away from science education practices focused on describing, measuring, and reporting about observable events or practices focused on transmitting countless discrete facts to students. While these documents may help in setting broad visions for science curricula and instruction, they do not provide the level of specificity necessary to help teachers enact particular practices in their classrooms. Our recent efforts with teachers seek to fill this gap by developing conceptual and pedagogical tools offering heuristic value for teachers to carry out specific instructional practices pressing for the co-construction of scientific explanations in science classrooms (Thompson et al., 2009b, 2009c, 2010; Windschitl et al., 2008a, 2008b, 2011).

### CONSTRUCTING SCIENTIFIC EXPLANATIONS WITH TEACHERS AND STUDENTS

When we imagine the practices that a science teacher uses to foster scientific explanation with students, we see a distinction between practices focused on helping students make sense of the explanations that they *consume* from authoritative sources like texts and teachers and dialogic practices focused on having students *produce*—not just *reproduce*—scientific explanations based on their own ideas and understanding of evidence. We have observed that constructing and evaluating scientific explanations is a challenge both for science students *and* for science teachers (Windschitl et al., 2008a, 2008b). Simply exhorting teachers to engage in a practice—no matter how valuable—does not make the practice happen. Teachers need scaffolding and support for learning how to engage in ambitious science teaching practices, but as a field we are just beginning to understand those supports for teacher learning. Along with our participating teachers, we have been wrestling with
these issues for over 4 years, and in many cases the teachers are only now beginning to gain insight into how the complex practice of scientific explanation can apply to the curriculum they use every day (Thompson et al., 2009b, 2009c, 2010; Windschitl et al., 2008a, 2008b, 2011). For these teachers, as well as for us, pedagogical decision making about scientific explanations in the classroom is not a straightforward task.

Five years ago, we began working with a cohort of novice teachers in graduate coursework focused on model-based inquiry geared toward constructing and refining scientific explanations with secondary students in Grades 6–12 (see Windschitl & Thompson, 2006, and Windschitl et al., 2008b, for details about the design of these courses). We thought we had guided our participants through a rich learning experience in the science teaching methods course, and we were really looking forward to seeing how our novice teachers engaged in ambitious science teaching in the classroom. After 20 weeks of coursework, our participants began a 10-week teaching practicum. Initially teachers struggled to enact the classroom practices necessary to engage their students in constructing evidence-based scientific explanations. We immediately realized that the Methods course had not fully supported their learning and started to create new supports. By working to support our novice teachers, we have deepened our own understanding of the complex practice of scientific explanation. Here we share an overview of our intellectual growth as well as some of the conceptual and pedagogical tools that are the tangible products emerging from 5 years of work with teachers. For more detailed accounts of our recent research, please see Thompson & Windschitl (2006), Thompson et al. (2009b, 2010), and Windschitl et al. (2008a, 2008b).

**Conceptual and Pedagogical Tools for Scientific Explanations in Classrooms**

In response to our beginning teachers’ struggles, we realized that we had to provide additional support in the form of conceptual and pedagogical tools—tangible tools and practices that would foster particular socioprofessional practices that, until this moment, we had vigorously espoused but had not facilitated. Our first move was the most critical: We explicitly defined for ourselves and for our novice teachers what attributes characterized “good” scientific explanations. We created a rubric—the Explanation Tool—delineating a simplified continuum of scientific explanations that (1) employ major scientific theories, (2) seek underlying theoretical causes for observable events in nature, and (3) when appropriate, utilize mathematical models to describe patterns in data (see Table 3). This Explanation Tool served as a powerful heuristic helping to organize our teachers’ thoughts about scientific explanations in their classrooms.

We chose to use a mixture of models for explanation for two important reasons. First, it is clear from both the philosophy of science literature and from studies of scientists at work that multiple forms of scientific explanation are employed in the actual practices of scientists. Second, to capitalize on teachers’ and students’ existing everyday epistemic and discursive practices, we found it necessary to create a variety of connections between everyday ways of reasoning and communicating and the specific practices associated with scientific explanation. This is a pragmatic approach to explanation similar to the view of Van Fraassen, but we also emphasize two models of explanation frequently: (1) causal explanations and (2) unificationist explanations. Our rationale for this emphasis is threefold. First, we are trying to foreground some of the commonalities of scientific explanation inherent in philosophy of science regardless of differences between subdisciplines. Second, engaging in the practice of constructing these explanatory models fosters sense making.
<table>
<thead>
<tr>
<th>Explanations with Theoretical Components</th>
<th>What</th>
<th>How</th>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>c Student describes what happened.</td>
<td>○ Student describes <em>how</em> or partial why something happened.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c Student describes, summarizes, or restates a pattern or trend in data without making a connection to any unobservable/theoretical components.</td>
<td>○ Student addresses unobservable/theoretical components tangentially.</td>
<td>○ Student explains <em>why</em> something happened.</td>
<td></td>
</tr>
<tr>
<td>○ Student can trace a full causal story for why a phenomenon occurred.</td>
<td>○ Student uses unobservable/theoretical components of a model to explain an observable event/phenomenon.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>○ Student uses powerful science ideas (like kinetic molecular theory) to explain observable events.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Explanations with Mathematical Components</th>
<th>What</th>
<th>How</th>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>c Student describes what happened.</td>
<td>○ Student describes <em>how</em> something happened.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c Student describes, summarizes, or restates a pattern or trend in data.</td>
<td>○ Student links observations to mathematical concepts in isolation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>○ For example: correlates the number of strings supporting a load in a pulley system with the effort to lift the load.</td>
<td>○ Student explains <em>why</em> a mathematical model accounts for a phenomenon.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>○ Student links observations to statistical or other mathematical models.</td>
<td>○ Student explains the links between observations and statistical or other mathematical expressions.</td>
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</tr>
</tbody>
</table>
for learners. Finally, the process of exploring a trajectory from describing “what” happened to explaining “how” and “why” events happen helps teachers focus their science curriculum on central, core ideas in science (Thompson et al., 2009c; Windschitl et al., 2011).

The Explanation Tool offered teachers a decidedly oversimplified framework for thinking about scientific explanations, but it also served an important heuristic purpose scaffolding teacher learning in three ways. First, the Explanation Tool was used during conversations with the cohort of teachers to propel teachers to examine the science content of their lessons. Some teachers began to critique lessons in their standard instructional materials because these lessons seemed to be missing key theoretical concepts or tended to focus exclusively on measuring and describing easily observed variables (Thompson et al., 2009b, 2009c). Second, teachers used the Explanation Tool to refine the questions that they posed to students during class and in written assignments. Some teachers used the Explanation Tool to help sort through the myriad questions in their instructional materials and selected questions that emphasized explanatory reasoning instead of questions asking students to recall facts or define words (Thompson et al., 2010; Windschitl et al., 2011). Third, teachers used the Explanation Tool to examine the possible lines of reasoning emerging from their middle school and high school students. Some teachers used the Explanation Tool to map out their learning goals in advance, and then to systematically analyze their students’ responses throughout a unit of instruction tracing lines of thought and modifying subsequent instruction (Thompson et al., 2010; Windschitl et al., 2011). The Explanation Tool is not a tool to be used in isolation. Socioprofessional practices such as discussions with other science educators, the systematic examination of students’ unfolding science ideas, and analyses of the instructional supports given to students coupled with a powerful heuristic like the Explanation Tool pushes teacher practice forward (Windschitl et al., 2011).

Teachers’ growth continued during the first year of professional teaching as their engagement with the Explanation Tool during collaborative inquiry group meetings continued. A second tool—a learning progression for teachers—was developed to help participants reflect on their own learning and their classroom teaching practices (see the Appendix). This learning progression, similar in format to a rubric, outlines continua of development across four areas, which were focal ideas during the teachers’ graduate teacher education program. This tool enabled reflective conversations between teachers, colleagues, and instructional coaches where teachers could reenvision their teaching practice and take steps to enact increasingly ambitious pedagogy (Thompson et al., 2009b, 2010). Interestingly, teachers who had struggled to engage in ambitious teaching practices at the beginning of the school year noted that the focus on scientific explanations helped them find a “back door” into model-based inquiry and helped them to locate the “big ideas” in their curricula that could serve as the focus of their instruction (Thompson et al., 2009b, 2010). Previously, both Model-Based Inquiry and the process of transforming mundane curriculum topics into big science ideas had been too daunting for many teachers to attempt consistently during student teaching and during the early months of professional teaching. A focus on scientific explanations, supported by conceptual and pedagogical tools embedded in the practice of collaborative inquiry with colleagues, seems to have served as an “on ramp” for many of our teachers, allowing them access to ambitious pedagogy, which otherwise would have been out of reach for many novices.

Our findings indicate that the tools served at least four valuable functions for teachers. The tools (1) embody a valued practice (e.g., scientific explanation), (2) are applicable across grade levels and subject matter subdomains, (3) represent practice in accessible language, and (4) provide descriptions of levels of performance from which teachers and
students can identify “where they are” and what constitutes the next levels of performance (Windschitl et al., 2011). The heuristic functions of conceptual tools for teaching offer science teachers and teacher educators an opportunity to reify ideas about what counts in science classrooms. The use of tools for teaching has enabled us to have important conversations about scientific practice and knowledge construction that have pushed our teachers’ thinking as well as our own thinking about scientific explanations. We now are focusing on a system of conceptual and pedagogical tools embedded in collegial practices with like-minded peers to support teachers’ development of ambitious science teaching practices. Our current and future work with preservice and early career science teachers explores the possibility that with well-conceptualized systems of tools and with the constant support of a group of colleagues, novice science teachers can accomplish ambitious forms of science teaching that are otherwise generally unattainable by novices and by many expert teachers as well.

SYNTHESIS

Science education reform literature makes numerous calls for teachers to create learning environments emphasizing scientific explanations and argument construction. But, without clearer, more articulated conceptualizations of explanation and argumentation, science educators do not have the guidance necessary to make these visions of reform a reality because to do so means assembling a repertoire of teaching practices that is currently well beyond the norms of practice in classrooms. We hope to spark conversation across the science education community regarding three questions: (1) What constitutes a “good” scientific explanation in science classrooms?, (2) What makes an explanation explanatory rather than descriptive?, and (3) How might we evaluate the merits of alternate explanations offered by students in classrooms?

The science education community has made some attempts at addressing the first two questions. Allusions to particular models of scientific explanation can often be found within the reform literature, but to readers who are not well versed in philosophy of science these details may go unnoticed. The field of science education can look to philosophy of science for helpful models of scientific explanation. In particular, we suggest focusing on five philosophical models of scientific explanation that are commonly part of students’ and teachers’ everyday ways of engaging in explanation of natural phenomena, which may mean opening a door to employing multiple models of explanation (see Table 1). While there is much disunity in the sciences about concepts like scientific explanation, there are some points of consensus that can help answer some of our questions. By explicitly engaging with the range of possible models of explanation and making a principled choice for the kind of scientific explanation desired in particular cases for school science, researchers may be in a better position to clarify salient features of the epistemic practices involved for teachers and for students.

We have found that the single most powerful conceptual tool for advancing science teachers’ practice is to provide a way for teachers to distinguish between descriptive and explanatory endeavors in science. Moving from an emphasis on “what” happens in the natural world toward and emphasis on both “how” and “why” events happen opens new trajectories for teachers working to develop ambitious repertoires of instructional practice in science classes. Teachers who help students develop explanatory models based on evidence and on major theoretical ideas in science can create learning environments where students engage in productive disciplinary discourse throughout an entire school year developing and refining “what counts” as a good theory, model, explanation, or argument together as a community.
Recently, we have uncovered a major challenge in helping teachers realize this vision. We know that for teachers to create learning environments where students engage in model-based reasoning it is important for teachers to work out for themselves the standards for explanatory power, adequacy of explanations, and the strength of argument construction. Using conceptual tools, like the Explanation Tool (see Table 3), teachers can engage in important intellectual work together by building and refining scientific explanations for phenomena central to the school science subjects that they teach. However, it is difficult for teachers who have completed this intellectual work to then follow students’ ideas as they emerge during classroom discourse. Instead, teachers work to bring students “on board” with the teachers’ ideas. This is a perennial tension between authoritative and dialogic approaches and continues to be worth serious examination by scholars in science education.

It is the third question—How do we evaluate the merits of alternate explanations offered by students in classrooms?—that seems to be most absent from discussion about scientific explanations in school science. When our research group discusses learning environments that press for scientific explanation, we are envisioning classrooms where teachers and students work together to co-construct scientific explanations in the form of explanatory models combining students’ ideas, science ideas, and the available evidence. But much of the literature about scientific explanation in schools tends to focus on enhancing teachers’ ability to clearly communicate well-established scientific explanations to students who will subsequently absorb and internalize them. This vision of science learning stands in stark contrast to the learning environments envisioned in science education reforms, which tend to prioritize shared knowledge construction in the science classroom.

Teachers who create learning environments where students are engaging in the process of constructing and refining scientific explanations for themselves will be confronted by situations where students have constructed a plausible, but ultimately incorrect, scientific explanation. These “alternative explanations” present a tough pedagogical dilemma. In science classrooms, it can be difficult, if not impossible at times, to provide students and teachers with sufficient access to theory and evidence to allow for reasoning through alternative explanations to ultimately arrive at an understanding consistent with current scientific thinking. Moreover, there are often very good reasons for students to hold tightly to plausible, even if ultimately incorrect, explanations for natural events. Science teachers we have observed, including the first author, frequently reflect that there are many days when students’ alternative explanations push teachers into a conceptual and pedagogical “corner” where it seems that the only way out is to tell the student that her explanation is incorrect and supply her with the correct explanation. This is not a desirable pedagogical move, but we have yet to develop adequate pedagogical tools to help teachers work with students’ plausible-but-incorrect scientific explanations.

One of the challenges faced by science teachers who attempt to build scientific explanations with students is that both teachers and students often construct explanations from partial understanding of science ideas, limited access to empirical data, and a wide range of tacitly held ideas about the natural world. We would like the science education community to engage in conversation about the fine line between engaging in sense making about established scientific explanations and building explanatory models in science classrooms—explanations that may ultimately include threads of partial understanding but also threads of alternative conceptions. Much work remains to be done to help teachers and students engage productively in the practice of constructing, testing, refining, and justifying evidence-based scientific explanations, and we look forward to further conversations in the field.

Science Education
## APPENDIX: TEACHER’S PERFORMANCE PROGRESSION FOR MODEL-BASED INQUIRY

<table>
<thead>
<tr>
<th>Ambitious Practices</th>
<th>Focus on topic or “things”</th>
<th>Focus on observable processes</th>
<th>Explanatory model focus (Aim for this!)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Selecting big ideas, treating them as models</td>
<td>Teacher selects objects or classes of objects to learn about in varying degrees of detail. In class, student goals are to describe, name, label, identify, using correct vocabulary.</td>
<td>Teacher selects as focus “what is changing” in a system or how conditions affect a naturally occurring event.</td>
<td>Teacher focuses on unobservable processes, events, or entities, or the relationships among science concepts. Ties these to important observable natural phenomena to develop explanatory model that students will study.</td>
</tr>
<tr>
<td>2) Attending to students’ initial and unfolding ideas</td>
<td>Monitoring, checking, re-teaching ideas</td>
<td>Elicits students’ initial understandings</td>
<td>References students’ ideas &amp; adapts instruction (Aim for this!)</td>
</tr>
<tr>
<td>Monitoring, checking, re-teaching ideas</td>
<td>Teacher primarly delivers information to students. Teacher engages in 1-on-1 tutoring, uses mainly IRE in whole class conversations, and uses students ideas to check for understanding (gets it/don’t get it).</td>
<td>Teacher elicits students’ initial and on-going hypotheses, questions, or conceptual frameworks about a scientific phenomenon.</td>
<td>Teacher develops rich tasks to elicit students’ initial conceptions of a scientific idea. Within and across lessons teacher purposefully uses students’ ideas to reshape the direction of classroom conversations, engineer productive classroom conversations, or pursue students’ lines of thinking across multiple lessons.</td>
</tr>
<tr>
<td>3) Investigating science ideas in the classroom</td>
<td>Primary focus on method</td>
<td>Discovering or confirming science ideas</td>
<td>Building concepts within investigations</td>
</tr>
<tr>
<td>Primary focus on method</td>
<td>Teacher asks students to identify variables and describe experimental set-ups. Science concepts are played down to afford time to talk about designing experiments. Talk with students is about error, validity, replicability.</td>
<td>Teacher has students “discover” science concepts for themselves (without much background ahead of time) OR has students use an activity as a “proof of concept.” Students not asked to draw hypotheses from scientific models or theories.</td>
<td>Teacher foregrounds key science concepts and asks students to use an investigation to make sense of the concepts. Focus is on sense making between data and developing science concepts as described earlier.</td>
</tr>
<tr>
<td>4) Pressing for explanation</td>
<td>No press for a scientific explanation</td>
<td>“What happened?” explanation</td>
<td>“How/ partial why” something happened explanation</td>
</tr>
<tr>
<td>No press for a scientific explanation</td>
<td>Teacher does not ask students to provide explanations; focus is on procedures of an activity only.</td>
<td>Teacher asks students to describe relationships between variables or differences between groups.</td>
<td>Teacher asks students to talk about relationships among variables or observations and how these play a role in a system of activity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Causal explanation (Aim for this!)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Teacher has students use theoretical events, processes, and entities to tell a causal story of why something happened (this may mean supporting students through “what/why explanations” with the end goal of working toward “why explanations”). Teacher also unpacks/scaffolds learning about the nature of scientific explanations with students, and “what counts” as evidence.</td>
</tr>
</tbody>
</table>
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REFERENCES


