JOURNAL OF RESEARCH IN SCIENCE TEACHING VOL. 53, NO. 7, PP. 1082–1112 (2016)

Research Article

Epistemologies in Practice: Making Scientific Practices Meaningful for Students

Leema K. Berland,[1] Christina V. Schwarz,[2] Christina Krist,[3] Lisa Kenyon,[4] Abraham S. Lo,[3] and Brian J. Reiser[3]

[1]*Curriculum and Instruction, University of Wisconsin, Madison, Madison, Wisconsin*
[2]*Teacher Education, Michigan State University, East Lansing, Michigan*
[3]*Learning Sciences, Northwestern University, Evanston, Illinois*
[4]*Wright State University, Dayton, Ohio*

Received 19 August 2014; Accepted 5 May 2015

Abstract: Recent research and policy documents call for engaging students and teachers in scientific practices such that the goal of science education shifts from students *knowing* scientific and epistemic ideas, to students *developing and using* these understandings as tools to make sense of the world. This perspective pushes students to move beyond the rote performance of scientific actions or processes and engage instead in purposeful knowledge construction work. This raises parallel questions about how to go beyond characterizing student performance of scientific process to understand their engagement in scientific practices as a goal-directed activity. To that end, this article offers a framework—the *Epistemologies in Practice* (EIP) framework—for characterizing how students can engage meaningfully in scientific practices. This framework emphasizes two aspects of student engagement in scientific practices: (1) the students' epistemic goals for their knowledge construction work and (2) their epistemic understandings of how to engage in that work. © 2015 Wiley Periodicals, Inc. J Res Sci Teach 53: 1082–1112, 2016
Keywords: scientific practices; modeling; argumentation; explanation; epistemology

There has been long-standing effort to shift science learning toward learning by *doing* science, rather than by merely learning *about* science ideas (DeBoer, 1991), apparent in an increasing emphasis on inquiry in science classrooms (Abd-El-Khalick et al., 2004; Duschl, 1990). Recent research has seen the goals of inquiry elaborated and clarified by efforts that view science as a *practice*, and call for engaging students and teachers in scientific practices in classrooms (Lehrer & Schauble, 2006; National Research Council, 2007). The National Research Council's *Framework for K-12 Science Education* (2012) casts science and engineering practices in a central role in its guidelines for the development of new science standards (NGSS Lead States, 2013). This "practice turn" (Ford & Forman, 2006) highlights that students should be engaged in the work of knowledge construction and evaluation, and that it is through reflective participation

Contract grant sponsor: National Science Foundation; Contract grant number: DRL-1020316; Contract grant sponsor: Institute of Education Sciences, U.S. Department of Education; Contract grant number: R305B080027.
Correspondence to: L. K. Berland; E-mail: leema.berland@wisc.edu
DOI 10.1002/tea.21257
Published online 8 June 2015 in Wiley Online Library (wileyonlinelibrary.com).

in scientific practices that students develop usable forms of both the epistemology underlying the scientific endeavor and explanatory scientific ideas (Duschl, 2008; Lehrer & Schauble, 2006). Thus, the emphasis on scientific practices as learning goals and as a pedagogical approach is designed to focus the attention of educators on students constructing and applying knowledge, rather than on student attainment of discrete scientific and epistemic ideas.

One step toward supporting student engagement in scientific practices is to help them know what to do. For example, many approaches to supporting students' active participation in scientific knowledge construction engage students in controlling variables (e.g., Chen & Klahr, 1999; Kuhn & Pease, 2008). Other approaches have made the structure of the products the students are creating more explicit. For example, much of the work analyzing and supporting students' argumentation has focused on making clear that students should support claims with evidence, provide warrants to support that connection, and that the best arguments contain rebuttals (Erduran, Simon, & Osborne, 2004; McNeill, Lizotte, Krajcik, & Marx, 2006; Sampson, Grooms, & Walker, 2010; Songer & Gotwals, 2012; von Aufschnaiter, Erduran, Osborne, & Simon, 2008). This work has shown much success in supporting students as they perform the focal process or construct the desired product. However, emphasizing the actions alone can result in rote performance and attainment of skills, rather than student engagement in the rich work of scientific knowledge construction, evaluation, and refinement (Chinn & Malhotra, 2002; Windschitl, Thompson, & Braaten, 2008)

Understanding science as participation in practices offers an explanation for these challenges: this perspective underscores that the work of science is part of an ensemble of activity such that the tasks are part of a coherent network of purposeful action (Christodoulou & Osborne, 2014; Lehrer & Schauble, 2006; Manz, 2012, 2014). For example, a scientific argument is a purposeful part of an ensemble of activity when the acts of justifying, evaluating, revising, and rebutting claims enable the community to construct knowledge (Ford, 2012). In contrast, constructing an argument as a stand-alone product to be evaluated by the teacher is "psuedoargumentation" in that the students are focused on "the instructions and satisfying the teacher [rather] than on the substance of the ideas" (Berland & Hammer, 2012a). In short, a practice-based approach to science education engages students in work that enables them to make progress "on communal objects and meet evolving goals" (Manz, 2014, p. 3) rather than by solely following directions or distinct memorized routines. Ford (2008) exemplifies the value of emphasizing the communal goals around which the ensemble of scientific activity is organized by demonstrating that students who understand the purpose of controlling variables are better able to determine when and how to do it than are students who learn the skills of identifying the variables to control and how. He called this richer understanding a "grasp of practice." A practice-based approach to science education pushes students to move beyond the rote performance of scientific actions or processes and engage instead in purposeful knowledge construction work—to develop a "grasp of practice."

This shift toward understanding and supporting students as they participate in scientific practices requires a similar shift in the work of researchers: we must now attend to "both what individuals do [i.e., testing hypotheses] and the hows and whys such practices are employed" (Calabrese Barton, Tan, & Rivet, 2008, p. 75). This raises important questions about how to study student engagement in scientific practices rather than solely those processes that are often part of the practices. This article builds on work demonstrating that students can meaningfully engage in the ensemble of scientific practices, and the value of this approach (Calabrese Barton & Tan, 2010; Engle & Conant, 2002; Ford, 2008, 2012; Herrenkohl & Guerra, 1998; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999; Jimenenez-Aleixandre, Rodriguez, & Duschl, 2000; Lehrer &

Schauble, 2006). We offer a framework—the *Epistemologies in Practice* (EIP) framework—to support researchers in characterizing student engagement in scientific practices. In this article, we describe and exemplify the EIP framework and conclude with a discussion of the implications of this framework for educators.

The Epistemologies in Practice Framework

When engaged in scientific practices there are many opportunities for students to make decisions—i.e., what steps to take, what to include in the knowledge product being created, what to pay attention to when constructing that product, who will evaluate and use their product, etc.—that lead to very different ways to engage in the practices. For example, when constructing a model of how light travels, middle school students have to decide what kind of information is needed in the model. They might think about including key components (i.e., including labels and light rays), incorporating their past experiences (i.e., they may have seen light bending in water), and/or considering how the system works (i.e., the interaction between light rays and the type of material through which it is traveling). In addition, students' understanding of why they are engaging in modeling in these ways can vary. For example, they might engage in modeling to satisfy expectations of an outsider (i.e., their teacher), or they might do so because they are actively trying to understand the phenomena under study (i.e., how light travels). The EIP framework characterizes these different forms of engagement including the students' often-implicit goals for their knowledge construction work and understandings of the kinds of information that will be useful and valuable in fulfilling these goals—in short, their epistemological understandings of the work at hand. This includes considering the decisions students make about their knowledge building, as well as how and why they are doing it.

We use the term epistemologies *in practice* to reference both the practice-based perspective of student learning and to emphasize that we are interested in students' epistemological ideas *in use* (or in practice). Thus, in using the term EIP, we mean to emphasize that the epistemic ideas guiding student work are a combination of ideas *and* action (Sandoval, 2014). These epistemic ideas are manifest in students' actions, decisions, and rationales—similar to Sandoval's (2005) "practical epistemologies"—and as such, their actions reflect underlying ideas or "rules of thumb" about knowledge construction and evaluation.

It is important to note that we are not making claims about the explicitness of the students' epistemic ideas. As Chinn, Buckland, and Samarapungavan (2011) argued in describing "epistemic commitments," one's epistemology is not necessarily explicit or conscious. For example, individuals may not be able to articulate *why* they are valuing one knowledge product over another, but the choices they make communicate an implicit rule of thumb or idea about what sorts of information is valuable in the current context.

In addition to understanding that students' EIP embody possibly implicit ideas and action, we also draw on Hammer and colleague's characterization of "epistemological resources" (Hammer & Elby, 2003; Louca, Elby, Hammer, & Kagey, 2004) and view epistemic ideas as contextualized, piecemeal ideas rather than coherent theories. Thus, the ideas that students draw on may change in response to the classroom norms, a teacher's meta-messages, problem constraints, available information, and so on (Hammer & Elby, 2003; Louca et al., 2004). For example, one can imagine a group of students productively working together to understand why their experiment failed in the ways that it did. This same group of students might then switch to a classroom goal orientation (i.e., recording the expected result) when the teacher reminded them of the remaining time. In this case, we would see the students' goals and actions changing from a focus on explaining how or why something happened to a more rote execution of the worksheet. And, as such, we do not argue that individuals consistently rely on a fixed coherent epistemological theory of how science or their classroom interactions should work. Rather, one's epistemology is made up of a flexible network of understandings that can be drawn from based on understandings of what is most appropriate and relevant to one's goals in the current setting.

The EIP framework expands on the extant literature on student epistemologies in two important ways. First, the EIP framework places an explicit emphasis on understanding the students' epistemic goals for their knowledge construction work, something that is often implicit or non-existent in other approaches. Second, we have narrowed the broad focus on "epistemology" to key epistemic considerations that are directly usable in the students' knowledge construction work. In the following sections, we expand on these two aspects of the EIP Framework: (1) the students' epistemic goals for their knowledge construction work, and (2) their epistemic understandings of how to engage in that work. We then describe the relationship between these aspects, arguing that a practice-based approach to science education requires that students use particular epistemic ideas to make progress on epistemic goals that are meaningful to the classroom and scientific communities. We call this target "meaningful use." We then illustrate how this approach and analysis for "meaningful use" can characterize engagement in scientific practices. We conclude with research and classroom implications.

Characterizing the Epistemic Goals of Students' Knowledge Construction Endeavors

Introducing disciplinary practices into a school culture faces challenges. In particular, analyses of classroom enactments of scientific practices suggest that teachers and students within a classroom community interpret disciplinary practices by adapting them to fit within their existing set of goals and expectations (Berland, 2011; Berland & Reiser, 2011; Calabrese Barton & Tan, 2009; Hogan & Corey, 2001). Moreover, classroom cultures that emphasize traditional school expectations over scientific knowledge construction goals can result in less productive adaptations of scientific practices (Berland & Hammer, 2012a; McNeill & Pimentel, 2010; Schneider, Krajcik, & Blumenfeld, 2005). Thus, we cannot assume that practices that enable progress toward the goals of the scientific communities will be experienced as meaningful—or goal directed—to the classroom communities that are adopting them. We, therefore, argue that educators and researchers must consider the ways in which the practices are (or are not) meaningful to the scientific and classroom communities in which they are enacted.

When characterizing this sense of "meaningfulness," we focus on the epistemic goals that hold the actions together as a sensible practice. Moreover, we begin with the disciplinary purpose —with the epistemic goals of scientific practices—because, if we want to foster student engagement in these disciplinary practices, we need to understand the ways in which they are meaningful to the scientific community. We then move on to explore what it means for these epistemic goals to be meaningful to the students in their classroom communities.

Meaningful to the Scientific Community. The broad purpose of the scientific endeavor is to construct general rules for how and why the natural world works in the ways that it does—to generate explanatory models (Giere, Bickle, & Maudlin, 2006; Lehrer & Schauble, 2006; Nersessian, 2002; Osborne, 2014; Passmore, Gouvea, & Giere, 2014; Russ, Scherr, Hammer, & Mikeska, 2008). Indeed, although investigations will emphasize various practices at different times (i.e., engaging in argumentation, designing investigations, analyzing data, and so on), these individual practices work together as an ensemble of activity to pursue the overarching goal of developing evidence-based, explanatory models of the how and why the natural world works in the ways that it does (Christodoulou & Osborne, 2014; Giere et al., 2006; Nersessian, 2002; Osborne, 2014; Passmore et al., 2014). For example, in order to describe how and why one can smell fresh coffee more noticeably than cold coffee, one could construct an explanation using the idea of motion of tiny odor particles bouncing off one other and off air particles, consequently traveling through space and spreading out over time through currents of air. However, another person might argue that this explanation does not account for the difference between smelling hot and cold coffee. This objection might encourage the first person to explain that when the object is at a higher temperature, its particles have more energy, and, therefore, they collide with and are bounced into more by the air particles, leading to a greater number of odor particles being spread out through the air, and more odor practices traveling to the person that detects them. She might also explain that air currents within the room help this spreading out happen faster and make the smell of the hot coffee more noticeable sooner. Throughout this process, we see the participants engaged in constructing mechanistic understandings of a natural phenomenon by arguing with and about their applications of a generalizable model of particle motion. Moreover, the individuals working to construct this explanatory account would be explicitly attending to many different goals throughout the process, but the goals would coalesce around the broad goal of constructing an explanatory model of scent traveling. As such, this is work that is consistent with general scientific sensemaking goals.

Meaningful to the Classroom Community. In addition to aligning with the epistemic goals of the scientific community, a practice-based approach means that students will be meaningfully engaged with these goals as well, or that they will engage "purposefully in curricular activities by adopting their goals and, thus, trying to learn the concepts or master the skills that they were designed to develop" (Brophy, 2008, p. 133). That is, a practice-based approach to science education asks that beyond performing actions that reflect the sensemaking goals of the scientific community, classroom communities will have adopted these goals for themselves.

When we refer to classroom communities as adopting epistemic goals that are meaningful to the scientific community, we use a specific meaning of "goal;" we are focused on students' perceptions of *why* they, as a class, are engaged in particular activities (similar to Barron et al., 1998). Ideally, if a student were asked: "Why are you doing this activity?" they would say, "To help us figure out how and why [a particular phenomenon] happens," rather than, "Because the teacher (or worksheet) asked us." Jimenenez-Aleixandre et al. (2000) similarly capture this sense of meaningfulness when differentiating between students who are "doing the lesson" (i.e., going through the motions to get a good grade or please [or appease] the teacher) and those who are "doing science." In other words, the practice-based approach asks that students experience their actions as purposefully moving toward a sensemaking goal.

We acknowledge that there are numerous factors that influence students' experiences and perceptions of their classroom goals. For example, schools tend to emphasize individuals' goals and achievements rather than classroom-level goals (Roeser, Midgley, & Urdan, 1996) and structure tasks and assessments for *performance* goals rather than mastery ones, which are more consistent with the meaningful forms of engagement we have targeted (Ames, 1992; Archer, 1994). In addition, dominant discourse patterns, such as the traditional I-R-E (initiation-response-evaluation) pattern (Lemke, 1990; Mehan, 1979) tend to maintain teacher control and decrease student autonomy (Herrenkohl & Guerra, 1998; Vedder-Weiss & Fortus, 2013), thereby reducing their perception of the science activities as "meaningful." And science, in particular, requires specialized ways using terms and expressing ideas, which can be alienating to students, particularly non-dominant ones (Ballenger, 1997; Lemke, 1990).

For each of these reasons, meaningful engagement in scientific practices requires transformation of classroom activities and activity structures. There is a wealth of research regarding how and why to engage in this transformation (e.g., Bang & Medin, 2010; Brown & Campione, 1996; Calabrese Barton & Tan, 2010; Herrenkohl et al., 1999; Rosebery, Warren, & Conant, 1992;

Scardamalia & Bereiter, 2006; Vedder-Weiss & Fortus, 2011, 2012). In addition to revealing the potential of transforming classroom practices in ways that make scientific practices meaningful, authors in this domain demonstrate that the epistemic goals of the classroom community emerge out of a dialectic interaction between individuals—and their individual backgrounds—and the classroom community, as a whole. As such, even with the a focus on transforming classroom practice to better enable meaningful engagement in scientific practices, the norms and goals of the classroom are emergent. Thus, we use the construct "meaningful to the classroom community" to mean not that all students find the same knowledge construction goal compelling at all times, but instead to communicate that the classroom activities are organized around a goal that the students understand and recognize as the type of goal that their classroom community tends to work towards. This requires that students be aware of the purpose of their actions and that they experience their actions as directed toward that purpose. As argued by Langer and Applebee (1986) "it is this sense of purposefulness that integrates the various parts of the task into a coherent whole" (p. 185–186).

Why Meaningful to Both the Scientific and Classroom Communities?. We argue that meaningful engagement in scientific practices requires developing alignment between the goals of the scientific community and the goals of the classroom community (see Figure 1). On one hand, emphasizing engagement in *scientifically* meaningful activities without attending to the meaning students are making of the activity is insufficient. This form of scientific engagement can result in the rote performance that is commonplace in classrooms. For example, controlling variables without a guiding research question might support students in developing requisite skills, but little understanding of when or why to utilize these skills (Ford, 2008). Similarly, enabling students to engage in the collaborative sensemaking that is central to scientific argumentation requires going beyond the typical approach of teaching the argument structure (i.e., using the Claim, Evidence, Reasoning framework) (McNeill, 2009). In short, this version of scientific activities can turn what could have been part of meaningful scientific practice into a rote activity students perform to demonstrate mastery of a skill (see the procedural science learning found on the left hand side of Figure 1). On the other hand, emphasizing engagement in activities that are meaningful to the *classroom community* (e.g., testing the strength of paper towels, or

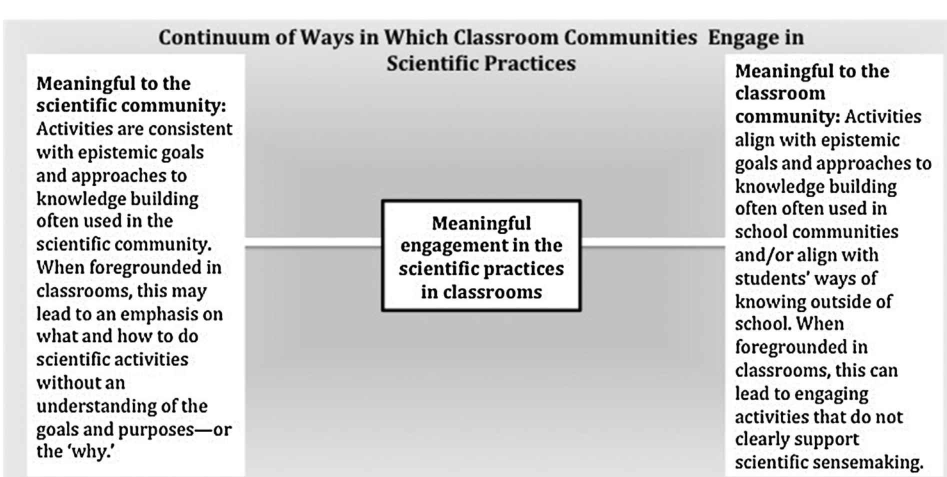

Figure 1. Continuum of ways in which classrooms engage in scientific practices.

developing songs to help memorize scientific vocabulary) is often motivating (and useful for many other non-science goals), but it might lack *scientific* meaningfulness (see the right hand side of Figure 1). For example, improving soap through trial-and-error rather than careful experimentation designed to elucidate chemical mechanisms turns what could have been a meaningful scientific investigation into a marketing project. Thus, although this activity involves scientific content, it might fall short of the vision of using practices to address core disciplinary ideas and develop understandings of the nature of science and science knowledge (National Research Council, 2007, 2012).

Our central point is that scientific practices need to engage the goals of both the scientific and classroom communities in order to be meaningful—that "meaningful engagement" in scientific practices requires a merging of the classroom and scientific communities' respective epistemic goals and ways of knowledge building. This merging would enable students to experience the goals of science as sensible within their classroom communities. Thus, one important aspect of the "practice turn" is an expectation that students' scientific work will cohere around a goal of constructing evidence-based, explanatory models of the how and why the natural world works.

Characterizing the Students' Epistemic Considerations

Thus far, we have argued that the practice turn requires that students be meaningfully engaged in the goal of constructing mechanistic understandings of natural phenomena. Doing this requires that students use epistemic ideas that are consistent with this goal—that their understandings of the kind of knowledge they are constructing and how they are doing it enable explorations of how and why the natural world works. Thus, we argue that students' engagement in scientific practices must also be characterized in terms of their underlying epistemologies. As such, the second key aspect of the EIP framework consists of the epistemic considerations that students use in their meaningful construction, evaluation, and revision of explanatory models.

While there are a variety of approaches to identifying and investigating students' beliefs about the scientific endeavor (Carey & Smith, 1993; Lederman, 2007; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Smith, Maclin, Houghton, & Hennessey, 2000), our long-term goal is to support students in enacting the ideas about the "forms of scientific knowledge" (Sandoval, 2005) that support their construction of that knowledge. Thus, consistent with Russ's (2014) argument, we focus on the epistemic considerations that are based in and guide actions toward knowledge construction (i.e., their "epistemologies for" knowledge construction) rather than on students' declarative statements regarding the scientific endeavor (i.e., their "epistemologies of" knowledge construction). To that end, we used two criteria when selecting the epistemic considerations to foreground in the EIP framework.

The first criterion for our epistemic considerations is that they have must have been identified as useful in the scientists' knowledge building work (Abd-El-Khalick et al., 2004; Duschl, 2008; Lederman, 2007). This ensures our continued connection to the scientific discipline. Our second criterion narrows this list by focusing on epistemic considerations that are apparent in, and useful to, students' knowledge construction endeavors. Forms of the epistemic considerations found in this framework first emerged as a key aspects of students' engagement in modeling in our earlier work developing a learning progression focused on the practice of scientific modeling (Schwarz et al., 2009; Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012). In this work, we found that students attended to multiple features of their models when developing and revising them, including the nature of the relationship between the model and the phenomena; the model's level of abstraction; the audience and clarity of communication; and evidence (Schwarz et al., 2012). In our current work, we hypothesized that general versions of these features could be similarly useful in students' general knowledge building and revising practices (explanation-formation, modeling, and argumentation). Thus, these features are the basis for our epistemic considerations.

In this way, while we were not working for students to develop understandings of scientific practices in the abstract, we are focusing on epistemic ideas that have been found to support the construction, evaluation, and use of explanatory models in science. Importantly, our epistemic considerations are not an exhaustive list of all epistemic considerations important in this knowledge building. Rather, they are our "best bets" regarding potential "leverage points" for understanding students' engagement in scientific practices.

By focusing on the usefulness to students and scientists when identifying the epistemic considerations found in the EIP framework, we bring the broad expectation that students will understand the scientific endeavor (or the nature of science) into alignment with a practice-based perspective on student science learning. That is, this emphasis on utility is designed to ensure that the epistemic ideas for which we analyze are the ones that most support students' engagement in sensemaking—they are the ideas with the most potential to be meaningfully connected to the students' knowledge construction endeavors. Based on these criteria, the EIP framework focuses on four epistemic considerations.

Before describing each consideration, we note two conscious choices we made when naming them. First, we focus on questions, not declarative statements, about knowledge. This emphasizes that each consideration represents a broad range of ideas and that students' considerations will change according to context (that they do not have a single "answer" to each consideration). Second, we use the general term "knowledge product" to refer to the shared knowledge that students construct, evaluate, and revise. We use this general term because the epistemic considerations on which we focus can apply to many different types of ideas or answers. For example, a "knowledge product" could be an explanation, a model, an argument, or a research question and could be represented physically, pictorially, verbally, or with computational tools. In addition, while the term "product" elicits images of final form knowledge, there are no truly final form knowledge products in science as our understandings are constantly evolving. Thus, the term could refer to any knowledge the students are constructing, evaluating, or revising. These knowledge products can be tentative and ephemeral or final and concrete. Some of the ways we have seen student address each consideration are summarized in Table 1, and each consideration is described in more depth below.

What Kind of Answer Should Our Knowledge Product Provide?. A key consideration in guiding the work of science knowledge building is the nature of the knowledge product or answer we are trying to develop (Giere, 1988; Henry, Breuilly, & Porter, 1997; Nersessian, 2002). We refer to this epistemic consideration as the *Nature* consideration. It is related to the forms and goals of the knowledge product. In short, the nature consideration refers to students' ideas about what counts as a sufficient answer to their current question.

The detailed content of this consideration emerged from our prior analyses of students' models and explanations (Schwarz et al., 2009; Schwarz et al., 2012) combined with literature examining the nature of mechanistic accounts and explanations (Braaten & Windschitl, 2011; Russ et al., 2008). There exists a range of products that students can generate and revise and each of these products aligns with implicit understandings about the nature of the knowledge product that is appropriate in the current context. For example, some products describe what happened in detail (e.g., a description of condensation could be "water appears on the outside of a cold can, and it drips down"), others identify key causal factors or articulate sequential descriptions of the phenomena without getting to the mechanism (e.g., a sequential account of evaporation that

Table 1
Epistemic considerations in students' Epistemologies in Practice

Epistemic Consideration	Range of Students' Considerations
What kind of answer should our knowledge product provide? (Nature)	• Our knowledge product should *describe* what happened in detail. • Our knowledge product should *explain how or why* something happened. In other words, it should articulate a step-by-step mechanism.
How does our knowledge product relate to other scientific phenomena and ideas? (Generality)	• Specific scientific phenomena do not relate to one another, so our knowledge product should characterize the specific nature of each individual phenomenon. • Generalized science ideas have little relationship to specific experiences or phenomena so our knowledge product should not connect across these ways of thinking. • Our knowledge products are created from and should explain a range of phenomena, so our knowledge product should show these connections.
How do we justify the ideas in our knowledge products? (Justification)	• We include the information in our knowledge products that others tell us to include (so it does not need to be justified). • We construct, evaluate, and justify our knowledge products using our interpretation of the available information (e.g., data, scientific theories, personal experiences, etc.)
Who will use our knowledge products and how? (Audience)	• Our knowledge product is for the teacher to evaluate our understanding. • We collaboratively construct and use our knowledge products with our audience.

identifies causal factors could be "when it is hot, water will evaporate and go into the air"), and still others articulate causal mechanisms that describe hypothesized (often non-visible) processes and objects in order to better *explain* the observable phenomena (e.g., a mechanistic account of condensation could be "When water particles in the air touch something cold, they will start to slow down, clump together, and turn into a liquid").

Students' rationales for their knowledge products can also offer more information about this epistemic consideration. For example, a student might state that they designed their model to "address how and why" the phenomenon occurred thereby aligning with a mechanistic understanding of the nature of their knowledge product or because they wanted "to show [i.e., *describe*] what was going on." These reflective accounts of the students' knowledge construction goals can be triangulated with the type of knowledge product they construct, or their evaluations of knowledge products, to develop richer accounts of the students' thinking about the nature consideration for each knowledge product.

How Does This Knowledge Product Relate to Other Scientific Phenomena and Ideas?. We refer to this as the *Generality* consideration; it relates to students' perception of whether and how specific phenomena or experiences relate to one another and to more general scientific ideas. While different knowledge products foreground different levels of abstraction (i.e., scientific models are often generalized accounts and explanations are often accounts of specific phenomena or classes of phenomena), an important aspect of science is to connect across these levels such that patterns in specific phenomena build general scientific ideas (often explanatory models) and explanations of specific phenomena are constructed using general scientific ideas (e.g., Kitcher, 1989; Lewis & Belanger, 2015; Strevens, 2008). These ideas have been echoed in much of the research articulating the practice of model-based reasoning (Passmore et al., 2014; Passmore & Svoboda, 2012; Schwarz et al., 2009; Schwarz et al., 2012; Schwarz & White, 2005; Stewart, Cartier, & Passmore, 2005), and in studies of epistemic ideas in science (see universality of ideas in Chinn et al. (2011)). In addition, the Claim, Evidence, and Reasoning framework (McNeill & Krajcik, 2008; McNeill et al., 2006) asks students to connect their claims and evidence with broader principles or empirical patterns of phenomena. This is an example of asking students to apply general scientific ideas to their understandings of specific phenomena. This epistemic consideration focuses on how students' view these relationships.

As students construct and evaluate knowledge products, we see variation in the degree to which they are concerned with connecting understandings of specific experiences or phenomena with one another and with general abstractions (what Beeth and Hewson (1999) refer to as "consistency"). For example, if students are treating their knowledge product as an account of a specific phenomenon with little relationship to generalized science ideas, they might focus primarily on the logical coherence of the explanation itself (i.e., when explaining how an invasive species impacted the other species in the ecosystem a student might say "the invader ate the rabbit's food" without connecting to general science ideas such as competition or predation). A student who was similarly de-emphasizing this relationship might alternatively focus on constructing an abstract model without explaining how it connected to specific phenomena in the world (i.e., a student could explain generally that "invasive species can cause other species to die out by competing with them for food and shelter" without grounding it in a specific example of competition). In neither case would the student be explicitly considering the relationship between abstract and specific knowledge. In contrast, a student who was viewing her knowledge product as connecting general and specific notions might emphasize these connections by defending her explanation of a specific phenomenon with a general science idea; showing the relevance of a general model by applying it to a specific phenomenon; or by explaining how multiple phenomena are accounted for in the knowledge product (i.e., in the invasive species example, the student could say "the sea lamprey competed with the trout for food and the invasive sheep competed with the rabbits. Both times the invader hurt other species by competing with them"). The generality consideration, therefore, highlights both whether and how students' knowledge products are becoming more general themselves, and whether or how students are using other situations or general ideas to create their products.

How Do We Justify the Ideas in Our Knowledge Products?. The third consideration focuses on students' thoughts about the justification of their ideas in their knowledge product, where those ideas come from, and their role in shaping the information used to construct their knowledge products. We refer to this consideration as the *Justification* consideration. The presence of the justification consideration itself is part of the shift from viewing science as answers to science as practice (Lehrer & Schauble, 2006; Smith et al., 2000). While a focus on supporting ideas with evidence and linking that evidence with the knowledge product has been a productive focus in bringing aspects of explanation and argumentation into classrooms (McNeill et al., 2006; Moje et al., 2004; Osborne, Erduran, & Simon, 2004; Sandoval & Reiser, 2004), students in traditional classrooms are rarely pushed to provide justifications for their ideas (Banilower et al., 2013).

We see evidence of a variety of implicit views about the justification of ideas throughout students' knowledge construction work. Sometimes students treat knowledge products as if the students are simply replicating the ideas that others have told them. In these instances, students would justify and evaluate knowledge claims based on their perceptions of accuracy or alignment with an authority such as a teacher or textbook (Carey & Smith, 1993) (i.e., "This is what we learned in class."). Sometimes students justify their ideas with empirical and theoretical information but do not treat that information as interpretable. In these cases, students would be treating the information in a more positivist manner as if the information itself made clear the students' ideas (Pluta, Chinn, & Duncan, 2011). For example, when defending a model, one student might state that his model is correct because "it is right there on the graph" or "that's what the experiment showed." Still other times students can treat the information (e.g., data, scientific theories, personal experiences, etc.) they are using to justify and construct their knowledge products as requiring interpretation and synthesis such that the students themselves are central actors in developing the ideas that ground their knowledge products. For example, a student could describe how the graph supports their knowledge product.

Who Will Use Our Knowledge Products and How?. We refer to this as the *Audience* consideration. This consideration reflects how students identify and orient their knowledge products for a particular audience and their understanding of how that audience will use their knowledge product. Work supporting student engagement in scientific argumentation as well as communication studies literature have revealed that student perceptions of the audience for their products influences how they engage in that work (Berland & Reiser, 2009; Forte & Bruckman, 2009; Hogan & Corey, 2001; Mcneill & Vaughn, 2010; Morgan & Beaumont, 2003; Paretti, 2009; Petraglia, 1995). For example, Berland and Reiser (2009) found that when students' written arguments suggested that they were working to persuade an audience of their claim, the students were more likely to include clearly identifiable evidence. One way to make students' classroom endeavors personally meaningful is by developing a classroom culture in which students have an audience that will use their knowledge products (Paretti, 2009).

Thus, in our EIP framework, we explore students' perceptions of their audience. Our prior work (Schwarz et al., 2012) indicates that students sometimes view their knowledge products as a way to show their teacher their understanding so their teacher can evaluate them. In these instances, students are viewing their teacher as their primary audience. This perception is made apparent when students focus on fulfilling criteria for their assignments without substantive conversation about what they think will be useful and why (i.e., a student might say "It says we need to have evidence. What is our evidence?").

At other times, students might consider an audience that could use their knowledge product. We see this perception occurring in two ways: in some cases, students might focus on an external audience that will use their knowledge product at some point, removed from the student author; at other times students will view their audience as a collaborator in the knowledge building. In the first case, students see their work as creating and revising knowledge products that articulate their current understanding to a curious audience (including peers or an external audience such as a scientist or community member) and that these products may help their audience figure something out. When students are working with this understanding of an audience, their conversations may emphasize clarity while rarely delving into substantive disagreements with one another (i.e., a student might explain a revision to their knowledge product by saying "because this shows it much better"). Students who are focused on an audience that will use their knowledge product might also discuss the needs and background knowledge of that community, ensuring that they are including the most helpful information (i.e., a student might say "not everyone knows what this means, lets define it").

In the second case, students might perceive their knowledge products as emerging through an evaluation and revision process that occurs within a knowledge building community. This perceived audience is different from the above because the audience is seen as a collaborator in the knowledge construction, such that the student is working with the audience to construct their knowledge products, justify their differing understandings, evaluate one another's ideas, and revise accordingly. In this view, the audience for the knowledge product is the student themselves as well as the other members of their knowledge building community. This approach to the audience epistemic consideration is made apparent when students explicitly address alternative ideas or account for the thoughts of their audience in the construction of their knowledge products. For example, when explaining why he added a path depicting where light would travel into his model of how light enables us to see, a student said: "If I didn't have a light pathway, it wouldn't show the light going to the [object]. And if it didn't show the light going to the [object], [someone else might] think it was going somewhere else. So I drew a light pathway going from the light to the [object] and then to the eye." This response indicates that the student understands there are possible alternative views, and he preemptively refutes them by providing deeper level mechanistic explanation.

In both cases—when students perceive an external audience and when they are considering a collaborative audience—students use their perceptions of that audience to guide the construction and evaluation of their knowledge products (Tindale, 1999). Thus, the audience consideration overlaps with and influences the other epistemic considerations.

While the perceived audience influences knowledge construction and the resulting knowledge product, attending to this audience does not require abandoning a scientific knowledge-building orientation, even if that audience is non-scientific. Instead, in order to communicate with an (non-scientific or scientific) audience while constructing scientific knowledge products, students must address both needs; the students' epistemic approach must enable scientific sensemaking while still attending to the needs of the perceived audience. For example, Calabrese Barton and Tan (2010) depict an out-of school program in which 10–14-year olds developed video documentaries that explained urban heat islands and their effect on the community. One might imagine that students doing this could focus on the school-ness of the task and de-emphasize their external audience. If students did this, their videos might include a mechanistic explanation using scientific terminology with little connection to personal relevance. On the other hand, students could engage in this task by focusing on how their peer community might receive their final video product. If students did this, the documentaries might be engaging and entertaining but include little scientific substance. Rather than either of these situations, students that participated in Calabrese Barton and Tan's study produced documentaries that were compelling to their peer- and community-based audience (i.e., they included music and interviews with community members that grounded the video in their lived experiences) and consistent with epistemic considerations that enable scientific sensemaking (i.e., they interpreted and used empirical data and connected generalized science concepts to explain the phenomenon). In this way, we argue that the students in this program enacted epistemic considerations that both satisfied the needs of their external audience and supported the scientific goals.

Relating the Epistemic Considerations. In examining these four epistemic considerations, we are claiming that students cannot engage in the work of science class without having ideas about each of them, even if they are implicit. For example, when answering a question in science, students are (probably implicitly) judging the kind of answer that they think they need to generate —students are determining whether a request for an explanation is a request for a mechanistic account, a clarification, or a defense of an idea (see Braaten and Windschitl (2011) for discussion of multiple uses of the word "explanation"). Similarly, when figuring out the answer to a question, students must decide whether to include their personal experiences, whether their answer should explicitly connect to yesterday's class activities, or whether a general definition will suffice.

Moreover, some of the epistemic ideas students may apply to their classwork are more powerful for constructing and evaluating knowledge in science than others. The following statements identify those perceptions for each epistemic consideration that best align with the scientific sensemaking goals of developing mechanistic accounts of natural phenomena:

- Nature: Scientific ideas are about showing how and why things happen. Considering this goal means that we need to follow the implications of each assertion others make, and be willing to flesh out the cause and effect story that explains the observations.
- Generality: Our new ideas need to fit with what we have already figured out and help us explain new situations. Considering this goal means we should figure out how specific examples we have seen fit with general ideas we are developing and learning.
- Justification: We must interpret the information available (e.g., data, scientific theories, personal experiences, etc.) to construct our knowledge products. Considering this goal means that we should evaluate our ideas as we develop them to make sure they fit our interpretations of that information, and we should provide those interpretations and the underlying information to help others see why the ideas can fit what we have seen.
- Audience: We build our scientific ideas together. Considering this goal means that we need to compare our ideas and work through all of the arguments, and we need to consider alternative ideas and try to address them when we communicate our knowledge products. This means that our audience helps us develop our knowledge products.

Notice that these four considerations work together. Building ideas together means we need to be able to evaluate our candidate knowledge products in light of others' work. This naturally leads to searching for justification from evidence so that we can compare the ideas in a principled way. The nature of the targeted knowledge means we need to push beyond description or simple association between variables, and consider more mechanistic accounts. The goal of doing this together complements the push for mechanism by motivating the comparison of competing mechanistic accounts of the same phenomenon. The sensemaking goals of science lead to searching for consistency with evidence and with ideas we have already developed.

Given that some perceptions of these epistemic considerations better support students in working toward the sensemaking goals of science than others, we argue that student work in the practices will improve as their perceptions of their work increasingly align with these ideas. Thus, as we study student engagement in scientific practices, their epistemic considerations are markers of that engagement.

In our emphasis on the students' EIP, we do not mean to negate the importance of content knowledge or practical skills. Instead, we see that an individual knowledge product (e.g., an explanation about why a particular population is decreasing or a model of predator/prey relationships) will improve as a result of students' increased content knowledge (e.g., understandings of relationships between organisms), their frequent engagement in relevant practices (e.g., identifying and analyzing data), and through their application of epistemic ideas that support the work of constructing explanatory models of natural phenomena (e.g., attention to evidence while striving to understand underlying mechanisms). Moreover, we hold that it is the students' epistemic considerations that will support them in engaging in the scientific endeavor around new content (i.e., as they shift from physics to biology or force and motion to magnets) and new practices (i.e., as they work to construct general models and specific explanations). This approach is consistent with Ford's (2006) notion of "grasp of practice" in which he argues that when students engage in purposeful investigations they are better able to apply scientific epistemic criteria to novel problems. Thus, while we recognize that content knowledge and knowledge of how to perform scientific activities are vital, we argue that there are additional key aspects of meaningful practice (i.e., the epistemic considerations) that must be supported if we are going to facilitate students' meaningful engagement in scientific practices.

Purpose of Epistemic Considerations

Combining the two aspects of the EIP framework—the students' goals for their knowledge construction work, and their epistemic considerations guiding how they engage in that work—we argue that engagement in scientific practices requires that students use ideas within the epistemic considerations in ways that are meaningful to them. Thus, we use the term *meaningful use* to focus our work on better understanding why the students use particular ideas within each epistemic consideration. *Meaningful use* of these epistemic ideas occurs when students frame (Berland & Hammer, 2012a, 2012b; Hutchison & Hammer, 2009) their work as engaging in a sensemaking task that is apparently guided by the ideas within each epistemic consideration (i.e., the ideas are a means to accomplishing a sensemaking goal that the students have adopted), rather then when they frame the activity as one in which the epistemic ideas are the ends in themselves. Thus, we contrast providing supporting evidence in a rote way because "the worksheet says we need evidence" from cases in which students provide evidence to help persuade their peers of their explanatory account. In both cases students are using the idea that evidence is relevant to their knowledge products but only in the latter is that *meaningful use*.

Moreover, while all ideas within the epistemic considerations will be useful depending on the student's goals, we are focused on the goal that is meaningful to the scientific community—that of constructing evidence-based, explanatory models of the how and why the natural world works. Thus, we are particularly focused on whether students' epistemic considerations are useful to both the scientific and classroom communities. As such, we use "meaningful use" to describe instances in which students are using epistemic ideas to support their endeavors to construct mechanistic understandings of natural phenomena (thereby being meaningful to the scientific community) and that they do so because they find the ideas to be useful to that goal (thereby suggesting that the work is meaningful to their classroom community).

In this way, the construct of *meaningful use* moves beyond the hope that students will simply *use* scientific criteria to fulfill external expectations. That sort of use is parallel to the rote performance of processes that are meaningful to the scientific community but are not meaningful to the classroom community (see the left-hand side of Figure 1). Instead, *meaningful use* suggests that the students have framed the activity as one in which the epistemic considerations help them work toward the goal of constructing scientific understandings. In these instances, their use of the epistemic considerations would suggest that their work in scientific practices is meaningful to both scientific and classroom communities (see the center of Figure 1).

Using the EIP Framework to Describe Students' Meaningful Engagement in scientific practices

In the following sections, we illustrate how the EIP framework can elucidate (1) the students' epistemic goals for their knowledge construction work and (2) the epistemic considerations guiding that work. In particular, we provide examples of students *meaningfully using* ideas related to the epistemic considerations in the EIP framework in ways that are consistent with the construction and evaluation of mechanistic understandings. Our goals in discussing these examples are to illustrate what meaningful use of these epistemic considerations looks like; and establish that it is possible for students to meaningfully use these considerations in ways that enable them to make sense of the world.

Before presenting these illustrative examples, a brief note on methods: When studying the students' epistemic considerations, we are examining how these ideas guide, and emerge, in the students' work—in their decision making regarding the construction and evaluation of scientific ideas. Thus, we do not see declarative statements of these epistemic considerations as sufficient evidence of their engagement in scientific practices or of their epistemologies in practice. Students might articulate an abstract idea such as reporting that scientists will change models (Carey & Smith, 1993; Grosslight, Unger, Jay, & Smith, 1991) or be able to explain the difference between a model and a theory (Lederman, 2007), but not necessarily use these abstract ideas to help them decide when and how to revise models (for example). However, having this knowledge without using it is inconsistent with the practice-based approach to science learning, which emphasizes students' knowledge in use. Moreover, we do not see declarative statements such as these as necessary. Students may have epistemological resources that generate intuitions about how to engage in scientific tasks that they cannot articulate as coherent or abstract statements (Hammer & Elby, 2003; Louca et al., 2004). Thus, in our analyses, we examine how students engage in the work of knowledge construction and evaluation and infer their underlying epistemic considerations and goals from this work.

Students in each of our examples are working with the *Investigating and Questioning Our World Through Science and Technology* (IQWST) (Krajcik, Reiser, Sutherland, & Fortus, 2013) or MoDeLS (Schwarz et al., 2009; Schwarz et al., 2012) curriculum materials, both of which are designed to support students and teachers in scientific practices. In both cases, students develop and use knowledge products, such as models or written arguments and explanations, as they work toward understanding a unit-anchoring phenomenon (Krajcik, McNeill, & Reiser, 2008). Using this approach, a driving question (i.e., the unit-anchoring phenomenon) motivates students' investigation, and provides a context in which students engage in scientific practices to make sense of or solve real-world problems. In neither curriculum are students explicitly told which epistemic ideas to apply and when. Instead, teachers work with the students to develop opportunities for them to make sense of their driving question through scientific practices. While the curriculum cannot ensure that student engagement in this work will be meaningful to the classroom community, the teachers with whom we worked were invested in this goal and actively fostered this engagement.

Example 1: Meaningfully Using Epistemic Considerations to Construct a Model

In our first example, we show a transcript of a group of 5th grade students from suburban Ohio as they construct a model of the phenomenon of condensation. We argue that students in this example are meaningfully using ideas related to multiple epistemic considerations. For brevity, our discussion highlights two of the epistemic considerations that appear most prevalently in their exchange: how their knowledge product relates to other scientific phenomena and ideas (generality); and who will use the knowledge product and how (audience).

In this case, the students are working through a unit on evaporation and condensation that emphasizes developing and revising explanatory models as a way to represent, compare, and reach consensus on their developing understandings (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011; Kenyon, Schwarz, & Hug, 2008). At this point in the unit, students have completed a number of class activities in which they observed the phenomenon of condensation and have investigated the conditions under which condensation occurs, identifying the presence of water vapor in the air and a temperature difference between the air and an object as key factors. They are now synthesizing those experiences to develop a model of how condensation happens. The excerpt in Table 2 begins as the students discuss whether they should use a particular object (i.e., a "pop can") in their model of condensation or an abstract "solid object."

Table 2
Students meaningfully using epistemic considerations to construct a model of condensation

Line	Speaker	Quote
1	Maria	Who thinks we should do the warm and cold pop cans?
2	Amee	I think we should just do one of them.
3	Jamie	Yeah, the cold water bottle.
4	Michael	I think we should do a solid object.
5	Amee	No.
6	Michael	To show at first that the liquid. . .to prove that the liquid comes from the air.
7	Jamie	Yeah. True.
8	Maria	But with the pop can, you can tell the liquid isn't pop.
9	Amee	But what solid object would we do? If we do a mirror then we would just do a square.
10	Jamie	If you're going to talk about pop, then it's just going to say pop. We're just going to say liquid, so it can be flexible.
11	Michael	I put a line and labeled it cold solid. I just drew an object.
12	Maria	I know, but we're figuring out [what examples to use] . . ., so we know that it's not coming from the can, it's coming from the air.

We highlight two epistemic considerations from the EIP framework that evident in this excerpt. The first is about the generality of their model. This consideration emerges as students argue about the object they should use in their model to represent the surface on which condensation occurs—whether it should be a "pop can" or a "solid object." In addition, the group members are discussing whether the contents of the container should be specific or general. In line 10, Jamie justifies that their model should say "liquid" instead of "pop" because it is "flexible." As such, these students are frequently shifting between discussing the specific phenomenon they studied (i.e., the pop can) and more abstract notions that suggest this experience can represent a class of phenomena (i.e., using a solid object instead of a water bottle, and liquid instead of pop). In this way, these students are ensuring that their knowledge product can account for multiple, related, phenomena. Moreover, in using the criteria that the model be "flexible" to justify a decision about their representation, Jamie is *using* the epistemic idea to accomplish the broader goal of constructing an explanatory model. Thus, her use of this idea connects her work to the larger ensemble of scientific activity: within the epistemic consideration of how the knowledge product relates to other knowledge, Jamie's work is meaningfully using the idea that a model should be general.

In contrast as is more typically observed in a classroom, Jamie might have said, "the teacher says we cannot use the word "Coke can," it has to be more flexible than that." If Jamie had said this to the group, her use of this epistemic idea that the knowledge product should account for multiple phenomena would not have represented "meaningful use" because this use would have suggested that Jamie did not experience this criterion as useful for her or her group's goals. Instead, in this case, Jamie would have been using the epistemic idea as an end—to demonstrate proficiency—rather than a means to accomplish the broader goal of constructing an explanatory model.

In addition to being concerned with creating a model that could be useful across a range of phenomena, Michael highlights the need to convince others that the condensed liquid originated from the air rather than the liquid inside of the container (lines 4–6), an idea they had considered in earlier class discussions but rejected. As such, Michael is recognizing that their product needs to be able to convince their audience of their proposed mechanism. Maria similarly makes the case that using a pop can could be more persuasive than using a container that contains a general "liquid," as it could easily show that "the liquid isn't pop" (line 8), implying that this might help convince the audience that the liquid must come from the air. These utterances suggest that within the epistemic consideration of who will use the knowledge product and how, both Michael and Maria are both using the idea that they have an audience with whom they need to collaboratively construct their knowledge product—that the knowledge product must respond to the needs of their audience.

Moreover, their use of this idea in order to justify their modeling choice suggests that they are *using* the idea in a *meaningful* way—they are using it to move forward in their scientific knowledge construction work—rather than simply following directions about what to put in their models. For instance, Maria could have easily said, "we have to include a general liquid because it says so in the directions." In this case, Maria would have been attending to the needs of her audience—the teacher—but not in a meaningful manner.

Example 2: Meaningfully Using Epistemic Considerations to Defend and Question an Explanation

In our second example, we share a transcript of a 5th grade class in which students are evaluating each other's explanations of a phenomenon related to the events of a simulated ecosystem. In this case, we see the students working to ensure that their final explanations are consistent with what was observed and to provide a coherent mechanism for those observations. In this way, we argue that the students' work reflects their perceptions of the epistemic considerations related to the sorts of answer their knowledge product should provide (nature) and how to justify the ideas in their knowledge products (justification).

This example is also drawn from a suburban classroom in Ohio. In this case, the students are working on the unit "Where Have All The Creatures Gone?," in which they are investigating interactions in ecosystems. In this episode, the students have worked individually, and are now in small groups, constructing and arguing for explanations about what is happening in a miniature-ecosystem simulated with the NetLogo computer program (Wilensky, 1999). The simulated ecosystem contains foxes, rabbits, grass, and an unknown invasive species (the invader). The students are using observations of this simulated ecosystem to explain how the invader affects the populations of foxes, rabbits, and grass. In particular, students are answering the questions: What does the invader eat? And, what (if anything) eats the invader? Students conduct multiple trials by populating the system with different starting sizes of each population and then introducing the invasive species to observe the results.

In this simulation, the rabbit, grass, and foxes co-exist in a stable cyclical relationship until the invader is introduced. When the invader is introduced the grass population decreases but maintains a cyclical relationship with the other organisms in the ecosystem, the foxes do not significantly change, and the rabbits tend to die out. One can use this data to support claims that the invader eats either (a) grass and rabbits or (b) just grass, depending on the mechanistic account one constructs. That is, students could argue that it eats grass and rabbits, which explains why both populations drop when the invader arrives. Students could also argue that the invader eats only grass, and the rabbits die due to competition from a more effective predator. Students can similarly use the data to defend claims about whether any organisms eat the invader.

The students in the exchange shown below (see Table 3) are using this data as they make sense of the invasive species' impact on this simulated ecosystem. The excerpt begins as Gretchen uses the available data to defend her claim that the invader eats grass.

This exchange begins with Gretchen using evidence to defend her explanation about what happened in this simulated ecosystem: When the invader enters the ecosystem (i.e., when she "launched the invasion") the invader ate the grass. Gretchen defends this claim with her observation that the rabbit and grass populations decreased significantly. We see her defending her

Table 3
Students meaningfully using epistemic considerations to defend and question an explanation of predator/prey relationships

Line	Speaker	Quote
1	Gretchen	Ok, we think that the invader eats grass because every single time that the invader, or we launched the invasion, both the rabbits and the grass went way down. .... So therefore, I'm assuming that the invader eats grass.
2	Daniel	Well, why wouldn't the invader die? That's my point. They're both eating it.
3	Gretchen	Please listen to me. OK, I'm guessing the invader can get the grass before the rabbits do. So they launch the invasion, and they're really hungry, so they eat up a ton of grass, but then not all the rabbits can get enough grass.
4	Laura	I agree with Gretchen but also I think the foxes eat the rabbits and foxes also eat the invaders so that...
5	Gretchen	See, I don't think that because the invaders never go down. They just keep coming up.

claim in line 5 when she responds to Laura's challenge by introducing additional evidence about the invader's population fluctuations (when she states "the invaders never go down"). These utterances indicate that Gretchen is using the evidence to justify her knowledge product. As such, Gretchen's work reflects the idea that empirical observations can be used to justify the knowledge product. Moreover, she draws upon the evidence without ever explicitly discussing external expectations. Instead, she is using it as part of the larger ensemble of scientific activity. We, therefore, argue that she is *meaningfully using* the evidence to guide her group's decision making about their final explanation. Conversely, suppose we heard Gretchen say in line 1, "both the rabbits and grass went way down, that is our one piece of evidence for our explanation so let's move on, what is the reasoning?" In this case, Gretchen would be demonstrating that evidence is relevant to her group's knowledge product, but not in the meaningful way she did during this small group discussion.

Second, students in this exchange are working to better understand the mechanism of this phenomenon. This is related to the epistemic consideration of the nature of the knowledge product—in this case students' comments suggest that they are looking for a knowledge product that provides a mechanistic account of the phenomenon. In the physical science case (Example 1), mechanistic reasoning involves developing a causal chain depicting the interactions of hypothesized non-visible components, molecules of water vapor in the air. In this population change scenario, mechanistic accounts require reasoning about the interactions of individual organisms (predation, survival, reproduction, death from lack of food) and developing a causal chain that explains population level changes from these individual interactions. For example, in line 2, Daniel responds to Gretchen by saying that she has not explained all of the available evidence—if the invader and the rabbits both eat grass, why did the invader population survive when the rabbit population died out? In this way, Daniel is questioning Gretchen's mechanistic account of what happened in the simulated ecosystem: how could an invasive species eating grass cause the observed population fluctuations? Gretchen responds to Daniel in line 3 in which she offers a refined mechanism: not only do the invaders eat grass, but they ate so much so quickly that the rabbits didn't have a chance to fight back (albeit leaving unstated the likely consequence of what happens to the rabbits if they don't get enough food). Thus, lines 2 and 3 suggest that Gretchen and Daniel have both moved beyond using evidence alone to ensuring that they have mechanistic accounts that can explain that evidence.

In this way, we see the student work reflecting the use of an idea related to a first epistemic consideration within the EIP framework: this knowledge product should explain how or why something happened. That is, they are working to construct mechanistic accounts of the available evidence. Thus, they are working in a way that aligns with the scientifically meaningful goal of constructing evidence-based, explanatory models. Moreover, these students are doing this without any allusion to fulfilling external expectations or because of an apparent belief that the goal of the exercise is to find evidence and construct a mechanistic account. Instead, they seem to be invested in solving the problem of figuring out the invader's role in the ecosystem—in other words they are constructing knowledge. Thus, we argue that these students are *meaningfully using* these epistemic ideas.

Example 3: Meaningfully Using Epistemic Considerations to Revise a Knowledge Product

The third example comes from a 5th grade classroom in Michigan working on the evaporation and condensation unit described in Example 1 (Baek et al., 2011; Kenyon et al., 2008). In this example from a student interview, we see a student (Seema) working to ensure that her final model is consistent with what she observed (i.e., the available data) and to provide a coherent mechanism for those observations. Moreover, she states that she is doing these things in order to construct a convincing model—thereby suggesting that she is using the idea that her knowledge product must respond to the needs of her audience. In this way, we argue that Seema is *meaningfully using* ideas related to the epistemic considerations of the kinds of answers the knowledge product should provide (nature), the way to justify it (justification), and who will use it (audience).

To illustrate this point, we use the following excerpt from Seema's interview about the model she finalized and revised at the end of the evaporation and condensation unit. In this excerpt, Seema explains why she has revised her final condensation model and included particular features in it. In particular, she is explaining why she added information to her model to show that the humidity in the air decreased when the water condensed, in addition to showing the water particles moving from the air and clumping together on the object.

> Well, it actually explains why the humidity [in the air] lowered. The humidity lowered because there was condensation [on the object]. That sort of proves that condensation is happening [from the air] because there is some evidence. Someone could think, "Oh, that [liquid from the object is] not [from] condensation. That's just the water from the cup seeping out." But then, if the humidity [in the air around that object] got lowered, it means that the water vapor [from the air] went on the cup. So that proves that [the water on the object is from water vapor] condensation and not the water seeping out.

As we can see in this quote, Seema included the level of humidity to demonstrate that the water that forms during condensation comes from the air (i.e., when condensation occurs the humidity levels on the outside of the condensing object decrease). In other words, she is using empirical evidence to convince others that the liquid appearing on the object is not the water "seeping out" of the container but is from the surrounding air. She continues later in the interview to make this same point. When asked whether she made "any changes to make your model more convincing?," Seema stated:

> Well, this [*pointing to the first model*], the explanation isn't that good. Someone could say, "That's not right. That's just the water seeping out of the cup," because I didn't put the humidity or anything. This [revised model] one, I put the humidity so that proves that it is water condens[ing from the water vapor]. I put in the evidence and I put in a better explanation, I explained why the humidity went down. So I think that would make someone say that it is accurate.

Throughout these interview excerpts, Seema describes how she modified her original model to make it more convincing by adding in empirical evidence, and providing a "better explanation" that is more mechanistic in that it shows "why the humidity went down." Thus, throughout this interview, we see clear evidence that Seema is *using* the ideas that empirical observations are relevant justifications for her knowledge product, and that it should explain how or why something happened (i.e., provide a mechanism). Moreover, this interview demonstrates *meaningful use* of these ideas because she is using these ideas as part coherent, purposeful practice—she is describes using the evidence and mechanistic account to convince her hypothetical audience, rather than out of a belief that models should include that information. In contrast, one could imagine a different interview for Seema, in which she might have said, "I revised the model to include the missing pieces. I made sure to include labels, evidence, and explanations, like humidity in the air lowered. My model is much better now that I have included all the necessary parts." In this case, the same epistemic ideas would have been applied without a clear connection to her, or her audience's, sensemaking goals and, as such this would have been a less meaningful use of the same ideas.

Summary of the Examples

These three examples reflect meaningful use of the ideas within the epistemic considerations because the students in each example appear to be guided by epistemic ideas that align with the sensemaking goals of science as a natural part of their knowledge construction work. That is, the students' perceptions of how and why to construct their knowledge products appear to emerge from their interpretation of how to make progress on their current goals, rather than from artificial constraints, such as expectations that they "use three pieces of evidence" or "label their models." Moreover, the students' justifications go beyond simply referring to task requirements. Instead, when making or justifying decisions about their scientific work (e.g., what to choose for the object on which water is condensing, or deciding to add evidence that the humidity in the air changed when condensation occurred), students refer to the consequences these decisions have for the clarity and persuasiveness of their ideas for others. As such, these three examples reveal that the epistemic considerations can indeed be used to guide students' knowledge building—that they have actual consequences for guiding practice.

Recall that we characterize student work as meaningful to both the scientific and classroom communities when students experience the sensemaking goals of science as sensible within their classroom community and view their work as making progress toward those goals. In each of the examples presented in this article, the learning environment (created through the curriculum and the classroom's enactment of that curriculum) attempted to bring practices that are meaningful to the scientific community into contact with the goals and ways of being that are meaningful to the classroom community. In analyzing classroom interactions, we similarly focused on cases in which students were exploring how and why the natural world works (i.e., meaningful to the scientific community), and then characterized whether that work was also meaningful to the students by examining the surrounding discourse and rationales for their work.

When attempting to engender and study instances in which student work is experienced as meaningful to the classroom and scientific communities, one could also imagine proceeding in the opposite direction. That is, one could design learning environments that work to bring goals, questions, and ways of being that are meaningful to students into contact with work that is meaningful in the disciplinary community (e.g., Bang & Medin, 2010; Calabrese Barton & Tan, 2010; Lee, 2006; Rosebery et al., 1992). Or, one could investigate cases in which students were engaged in work that grew out of their individual goals and ways of being and then explore connections between that work and work that is meaningful to the scientific community. For example, in a multiyear case study of a 4th–6th grader's engagement in science activities in and out of school, Bricker and Bell (2014) described how work that was meaningful in her home-life (e.g., mixing perfumes using a chemistry kit) made contact with, and supported, her participation in scientific practices in school.

It is important to note that regardless of the starting point—be it bringing the work that is meaningful to the scientific community into contact with the classroom community's goals and ways of being; or finding ways to involve scientific goals and ways of being into work that is meaningful with the classroom community (and individuals within that community)—the end result is student participation in work that is recognizable and sensible to *both* communities. It is this dual meaningfulness for which the EIP framework—and, more importantly, the practice turn in science education—argues.

Discussion

The EIP framework is designed to support researchers as we work toward the vision of the NRC (2012) by studying student engagement in scientific practices. As we have argued throughout, the shift toward envisioning scientific learning as occurring through and about scientific practices requires that students engage in work that is not only aligned with the goals and methods of the scientific community, and that is also meaningful to the classroom community. We have argued that one aspect of this meaningfulness is that learners take on the sensemaking goals of science and experience their work as making progress toward these goals.

The EIP Framework Attempts to Distinguish Meaningful Practice From Rote Performance

This emphasis on meaningful engagement in scientific practices builds on multiple strands of earlier research literature in science education, educational psychology, and the learning sciences. Expectancy-value-theory explores the relationship between student perception of the value—or usefulness—of their work and the effort they put into that work (Eccles & Wigfield, 2002). This body of research finds that students have increased motivation when they see their work as supporting their goals. In other words, students are more motivated when they find their work to be meaningful. Others have developed theories that can characterize the goal of student engagement in disciplinary practices. For example, Schaffer and Resnick (1999) introduced the term "thick authenticity" to describe the ways that student work is or is not connected to the students' goals and those of the discipline. Berland and Hammer's (2012b) discussion of "pseudoargumentation" focused on the meaningfulness of a particular practice, differentiating between student argumentation that is designed to fulfill a teacher's expectations and argumentation that emerges as part of a purposeful endeavor. Jimenenez-Aleixandre et al. (2000) similarly differentiated between students "doing the lesson" and "doing science." Still other researchers have created frameworks and principles to support students in finding scientific practices meaningful. For example, Edelson's (2001) Learning-for-Use framework and Engle and Conant's (2002) strategies for supporting students' "productive disciplinary engagement" both address ways that engaging with the ideas in particular disciplinary ways can become a tool for students to achieve goals they have taken on, instead of being perceived as arbitrary extrinsic constraints. And other work has explored ways to make student engagement personally meaningful by using students' cultural practices to bootstrap sophisticated engagement in science activities (e.g., Aikenhead, 1997; Bricker & Bell, 2012; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001), or to develop student agency in pursuing goals that make contact with the students' identity and non-school communities (e.g., Calabrese Barton & Tan, 2010; Cornelius & Herrenkohl, 2004).

Our EIP framework builds on this expansive literature base by operationalizing what we, as a community, mean when we ask students to engage in scientific practices in ways that are "thickly authentic," or to "do science." Our goal here is to rigorously distinguish between students going through the motions of providing evidence or articulating mechanisms only to fulfill a school goal and students investing in knowledge building work that foregrounds disciplinary sensemaking goals. Concretely, the EIP framework examines the epistemic considerations that students use in their scientific knowledge construction. In addition, the construct of "meaningful use" foregrounds explorations of students' understandings of *why* they are engaging in the work they are doing and how the epistemic considerations relate to their work. Thus, the EIP framework offers an analytical approach for understanding students' engagement in scientific practices that is meaningful to both the scientific and classroom communities.

We suggest that this approach addresses key questions about how to study student engagement in scientific practices rather than enacting processes that are often part of the practices for two reasons. First, this framework identifies and unpacks four epistemic considerations that are central for scientific knowledge construction (i.e., nature, generality, justification, and audience) to identify not only the epistemic ideas most utilized (or argued for) in science knowledge construction writ large (i.e., generalized mechanistic accounts that are justified with empirical evidence and build on existing ideas in science for an audience that is working with you to make sense of the phenomena) but to examine the range of ways that students are tackling their work. In other words, our examination of students' epistemic considerations moves beyond a binary examination of whether students' work represents an idealized form of science by characterizing the epistemic ideas that are relevant to the students' knowledge construction work.

Second, the EIP framework focuses researchers on the purpose students have in doing their work in a manner that moves beyond the structural forms of the practices. The framework not only points to what students are doing (are they identifying evidence?) but equally important, the framework suggests examining the ways in which student work reflects engagement in the larger ensemble of scientific activity. For example, we examine how and why particular epistemic ideas emerge in the students' work—are they identifying evidence to fulfill an external expectation or to persuade a classmate of their thinking?

Embedded in this approach is an understanding that we must distinguish students possessing knowledge *of* the scientific endeavor from more meaningful practice in which these ideas are used to engage in knowledge construction (Russ, 2014). Decontextualized examinations of students' epistemologies that assess students' "abilities to talk epistemologically about science" (Sandoval & Morrison, 2003, p. 369) may strongly underestimate whether and how those ideas are influencing and guiding students' work in the science (Bell, Blair, Crawford, & Lederman, 2003). Indeed, it is much simpler to repeat ideas such as "claims need to be supported with evidence" than to operationalize these ideas by using them to evaluate evidence for its fit with a claim, consider the strength of evidence, and so on. The EIP framework attempts to capture whether students know epistemic ideas (e.g., evidence is interpreted) by examining whether they are able to use these ideas (e.g., identify how evidence can play a role in teasing apart competing accounts, or uncover gaps in models that lead to new research questions) toward appropriate end.

Implications for Educational Practice

Attempts to scaffold students in engaging in the work of science often focus on helping students keep track of the components of the work. For example, the structure of a lab report encourages students to engage in and report on the elements of an investigation—such as question, method, findings, and conclusions. We agree that it is important for students to learn *how* to do these processes and to learn the format of the products. However, the concept of "meaningful use" in the EIP framework suggests that this is not sufficient—that the sole emphasis on the procedures or form of science is likely to support student work that is meaningful to the scientific community, but that is not also meaningful to the classroom community (see the left hand side of the continuum in Figure 1). As explained by Brousseau (1984) "the more explicit I am about the behavior I wish my students to display. . .the more likely they will take the form for substance" (quoted in Mason, 1989, p. 7).

Indeed, from this perspective, *scaffolding can be a double-edged sword*: while it can help students do all the steps of the work, or create products that contain all the necessary pieces, it can also have the unintended effect of making these actions (e.g., labels on diagrammatic models, evidence in an argument) experienced as ends in themselves, rather than as means. In this way, scaffolding the structure or steps of scientific practices can result in students simply "going through the motions" because they are laid out that way by the teacher and curriculum materials (Paretti, 2009; Petraglia, 1995); that is, "doing the lesson" (Jimenenez-Aleixandre et al., 2000). Labeling models and providing evidence for claims are steps toward developing understandings of how and why the natural world works in the ways that it does because these steps can help communicate ideas and convince an audience of the fit between the proposed idea with the evidence that has been collected. However, the "steps" of scientific practices are just one way to help accomplish this broad sensemaking goal. Moreover, fulfilling the steps does not ensure that the broader goals have been met, unless learners experience the steps as making progress toward the broader sensemaking goal.

Indeed, part of the role of scaffolding is to support students by making tasks more tractable, such as through structured materials or prompts that remind them of important steps to take (Reiser & Tabak, 2014). However, another key role for scaffolding is pushing students to attend to complexity that they might be likely to gloss over (Reiser, 2004). Teachers' moves or the structure of the task may need to *problematize* aspects of the task so that students go beyond treating the task as a series of routine steps, and engage in working through difficulties that are productive for learning (Kapur & Bielaczyc, 2012). Thus, we suggest that participating in scientific practices requires that learning environments focus on the practices as part of a coherent network of activities through which learners can build knowledge in science.

For example, the EIP framework suggests that we, as educators, must go beyond asking students to report evidence that supports their explanations and models. Instead, we must create situations and strategically support practices in which aligning with critical pieces of evidence helps students make progress on a particular goal they share—such as understanding the mechanisms of a phenomenon (e.g., Passmore et al., 2014; Passmore & Svoboda, 2012). This approach builds on past recommendations including Edelson's (2001) Learning-for-Use framework that posits that individuals learn best when the content they are learning helps them figure out a question they have identified or helps them solve a problem. Other studies have applied this theory to learning science content through design challenges (Kanter, 2010; Kolodner et al., 2003). These studies each offer design strategies for creating classroom contexts that make the target content necessary for students' successful engagement in their course projects—for making the target content a means rather than an end.

It is important to consider what may be needed to support students' meaningful engagement in scientific practices in this way. In this article, we have focused on classrooms that were in process of attempting to incorporate scientific practices in order to explore contexts that were amenable to the epistemic goals and considerations we have taken on as a focus of study. Teachers in these classrooms committed to using curriculum materials that reflect scientific practices (Kenyon et al., 2008; Krajcik et al., 2013). However, this should not be viewed as suggesting that curriculum materials alone are a strategy for engaging students in meaningful scientific practices. These recommendations for meaningful practice require creating a classroom culture that establishes sensemaking goals—that establishes the goals of incrementally building and refining mechanistic explanatory models, and makes the epistemic ideas that support this type of work sensible. It is not possible to do this through curriculum materials or particular teaching strategies alone. In fact, as we have argued, these recommendations require more than simply structuring learning tasks to align with practices; structuring activities that require the shape of disciplinary practices (e.g., asking students to present and critique each others' explanatory models), without the goals and norms that make such activities sensible are not sufficient (Hogan & Corey, 2001). Indeed, studies of interventions utilizing curriculum materials show a wide range of alignment with the practices they are meant to reflect, depending on the interpretation of these materials by the classroom community and their existing norms for interacting (Berland, 2011; Berland & Reiser, 2011; DeBarger, Choppin, Beauvineau, & Moorthy, 2013; McNeill & Krajcik, 2009; McNeill & Pimentel, 2010). Classroom norms that enable scientific sensemaking are co-developed as teachers and students engage in that sensemaking and curriculum materials that reflect those norms are only one component of the complex system that enables classroom communities to develop and sustain these norms (Bielaczyc, 2013; Herrenkohl et al., 1999).

Implications for Future Research

In this article, we have argued for an EIP approach to characterizing student work in scientific practices. We have presented an argument for the importance of distinguishing meaningful engagement in scientific practices from school science and from decontextualized knowledge about science. We have presented several examples that support the feasibility of students engaging in this type of practice, and the utility of this framework for analyzing aspects of meaningful engagement. These arguments raise a number of issues that provide direction for future research on scientific practices.

We have found that the four epistemic considerations discussed in this article provide a useful lens into student understandings of their knowledge construction work in science, and that it is possible for students to meaningfully use these understandings. However, the epistemic considerations do not provide an exhaustive list of all the epistemic aspects, beliefs, or values that can influence student work in the moment. For instance, these four considerations do not explore the relationship between student work in scientific practices and the social dynamics in their class, their role in the group discussions, or the understandings about things like importance of creativity. Thus, we present these particular considerations as working hypotheses from which to build and refine studies of students' implicit and explicit epistemologies about knowledge construction work in science class. Unpacking these epistemic considerations further will enable researchers to better understand and (eventually) support student engagement in meaningful scientific practices.

Additional research should also focus on relationships between the epistemic considerations themselves. As seen in the examples presented in this article, individual epistemic considerations rarely stand-alone. Recall Example 2 in which the students' search for a mechanistic account co-occurred with their use of evidence. The co-occurrence emerged out of the question: we have this evidence and this claim, is there a mechanistic account that can explain how the evidence resulted in the claim? Thus, we see that attention to evidence motivated a need to improve their mechanistic account of the phenomenon under study. Similarly, in other examples, the students' attention to an external audience drove them to apply more scientific understandings of other epistemic considerations. For example, Amee uses the idea of an external—non-teacher—audience to defend her decision to make a more general model in Example 1. And, in Example 3, Seema states that using evidence makes her model more convincing to others.

Through each of these examples, we see the possibility that the epistemic considerations might support one another and that they may be able to help build on one another over time. In this way, the epistemic considerations might "bootstrap" one another toward epistemic ideas that increasingly align with scientific sensemaking goals. Early analysis of some of our work indicates this may be the case (Schwarz, Akcaoglu, Ke, & Zhan, 2013). Thus, future work should explore these potential relationships—and others such as determining whether particular pairings are productive or whether one epistemic consideration supports each of the others. Understanding these underlying relationships and how they may develop over time may help educators better leverage their time and efforts when supporting student engagement in practices that are meaningful to both the scientific and classroom communities.

Another important research question concerns how students develop these epistemic considerations, and how to support that learning. Investigating this question will require examining the relationship between epistemic considerations and meaningful practice. While we have talked about the role of epistemic considerations as being able to guide more meaningful engagement in scientific practices, we do not mean to suggest that these should be learned first or separately in order to result in more effective practice. Engaging in meaningful activity creates a productive environment in which to develop these epistemic ideas and truly understand what they mean, in practice. We argue for the need to consider how the understanding and the doing are mutually supportive rather than attempting, for example, to assess epistemological understanding apart from its role in practice.

Finally, the EIP framework offers a way to focus our analyses of student engagement in the scientific practice by highlighting five key characteristics of that engagement (i.e., their purpose and each of the four considerations). In doing so, we have focused on individual or classroom perceptions of the practices without investigating the broader context in which the work is occurring. Moreover, as highlighted by sociocultural theories of learning from which the practice-based perspective emerges (Bang & Medin, 2010; Brown & Campione, 1996; Calabrese Barton & Tan, 2010; Herrenkohl et al., 1999; Rosebery et al., 1992; Scardamalia & Bereiter, 2006; Vedder-Weiss & Fortus, 2011, 2012), practices are constrained and made meaningful by the socio-material context in which they are enacted. Thus, a key next step is to investigate that context. That is, as described, the practice-based approach is "desettling expectations" (Bang, Warren, Rosebery, & Medin, 2012) in that it highlights the need for creating a hybrid space in which the epistemic considerations that are meaningful to the scientific community are valued and used by the classroom community. However, in many ways, these epistemic considerations are largely "settled" in that they represent Western science (Bang et al., 2012). Thus, additional research is required to explore the epistemic considerations and goals that become meaningful within their classroom communities and to understand the relationship to those of the scientific community.

We offer the EIP framework as an approach to characterize key aspects of disciplinary practices that can help communities of classroom learners experience these practices as meaningful. As such, we suggest the framework can help work toward a more meaningful form of school science in which students work together, using their own version of scientific practices in a meaningful way, to engage in scientific knowledge building.

This research was funded by the National Science Foundation under grant DRL-1020316 to the Scientific Practices project at Northwestern University; the Institute of Education Sciences, U.S. Department of Education, through Grant R305B080027 to Northwestern University; and the American Educational Research Association Minority Dissertation Fellowship Program. We also appreciate the work of Hamin Baek, Kathleen Crucet, Mackenzie English, Li Ke, May Lee, Jeannette Manger, Josh Rosenberg, and Amber Todd for their related work on this project. The opinions expressed herein are those of the authors and not necessarily those of the NSF, IES, or AERA.

References

Abd-El-Khalick, F., BouJaoude, S., Duschl, R. A., Lederman, N. G., Mamlok-Naaman, R., Hofstein, A., & Tuan, H. -l. (2004). Inquiry in science education: International perspectives. Science Education, 88(3), 397–419.

Aikenhead, G. S. (1997). Toward a first nations cross-cultural science and technology curriculum. Science Education, 81(2), 217–238.

Ames, C. (1992). Classrooms: Goals, structures, and student motivation. Journal of educational psychology, 84(3), 261.

Archer, J. (1994). Achievement goals as a measure of motivation in university students. Contemporary Educational Psychology, 19(4), 430–446.

Baek, H., Schwarz, C. V., Chen, J., Hokayem, H., & Zhan, L. (2011). Engaging elementary students in scientific modeling: The MoDeLS fifth-grade approach and findings. In M. S. Khine & I. M. Saleh (Eds.), Models and modeling in science education (Vol. 6, pp. 195–218). Dordrecht: Springer.

Ballenger, C. (1997). Social identities, moral narratives, scientific argumentation: Science talk in a bilingual classroom. Language and Education, 11(1), 1–14.

Bang, M., & Medin, D. (2010). Cultural processes in science education: Supporting the navigation of multiple epistemologies. Science Education, 94(6), 1008–1026. doi: 10.1002/sce.20392

Bang, M., Warren, B., Rosebery, A. S., & Medin, D. (2012). Desettling expectations in science education. Human Development, 55(5–6), 302–318. doi: 10.1159/000345322

Banilower, E., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weiss, A. M. (2013). Report of the 2012 national survey of science and mathematics education (pp. 1–309). Chapel Hill, NC: Horizon Research Inc.

Barron, B., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., & Bransford, J. D. (1998). Doing with understanding: Lessons from research on problem- and project-based learning. Journal of the Learning Sciences, 7(3–4), 271–311.

Beeth, M. E., & Hewson, P. W. (1999). Learning goals in an exemplary science teacher's practice: Cognitive and social factors in teaching for conceptual change. Science Education, 83, 738–760.

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. Journal of Research in Science Teaching, 40(5), 487–509.

Berland, L. K. (2011). Explaining variation in how classroom communities adapt the practice of scientific argumentation. Journal of the Learning Sciences, 20(4), 625–664.

Berland, L. K., & Hammer, D. (2012a). Framing for scientific argumentation. Journal of Research in Science Teaching, 49(1), 68–94.

Berland, L. K., & Hammer, D. (2012b). Students' framings and their participation in scientific argumentation. In M. S. Khine (Ed.), Perspectives on scientific argumentation (pp. 73–93). Dordrecht, The Netherlands: Springer.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. Science Education, 93(1), 26–55.

Berland, L. K., & Reiser, B. J. (2011). Classroom communities' adaptations of the practice of scientific argumentation. Science Education, 95(2), 191–216.

Bielaczyc, K. (2013). Informing design research: Learning from teachers' designs of social infrastructure. Journal of the Learning Sciences, 22(2), 258–311. doi: 10.1080/10508406.2012.691925

Braaten, M., & Windschitl, M. (2011). Working toward a stronger conceptualization of scientific explanation for science education. Science Education, 95(4), 639–669. doi: 10.1002/sce.20449

Bricker, L. A., & Bell, P. (2014). "What comes to mind when you think of science? The perfumery!": Documenting science-related cultural learning pathways across contexts and timescales. Journal of Research in Science Teaching, 51(3), 260–285. http://doi.org/10.1002/tea.21134

Bricker, L. A., & Bell, P. (2012). In M. S. Khine (Ed.), Argumentation and reasoning in life and in school: Implications for the design of school science learning environments (pp. 117–133). Dordrecht, The Netherlands: Springer.

Brophy, J. (2008). Developing students' appreciation for what is taught in school. Educational Psychologist, 43(3), 132–141. doi: 10.1080/00461520701756511

Brousseau, G. (1984). The crucial role of the didactical contract in the analysis and construction of situations in teaching and learning mathematics. In H. -G. Steiner (Ed.), Theory of mathematics education (pp. 110-119). Occasional paper 54. Bielefeld, Germany: University of Bielefeld, Institut ffir Didaktik der Mathematik. Bruner, J. (1986). Actual minds, possible.

Brown, A. L., & Campione, J. C. (1996). Psychological theory and the design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), Innovations in learning: New environments for education (pp. 289–325). Mahway, NJ: Erlbaum.

Calabrese Barton, A., & Tan, E. (2009). Funds of knowledge and discourses and hybrid space. Journal of Research In Science Teaching, 46(1), 50–73.

Calabrese Barton, A., & Tan, E. (2010). We be burnin'! Agency, identity, and science learning. Journal of the Learning Sciences, 19(2), 187–229. doi: 10.1080/10508400903530044

Calabrese Barton, A., Tan, E., & Rivet, A. (2008). Creating hybrid spaces for engaging school science among urban middle school girls. American Educational Research Journal, 45(1), 68–103.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. Educational Psychologist, 28(3), 235–251.

Chen, Z., & Klahr, D. (1999). All other things being equal: Acquisition and transfer of the control of variables strategy. Child Development, 70(5), 1098–1120.

Chinn, C. A., Buckland, L. A., & Samarapungavan, A. (2011). Expanding the dimensions of epistemic cognition: Arguments from philosophy and psychology. Educational Psychologist, 46(3), 141–167. doi: 10.1080/00461520.2011.587722

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. Science Education, 86(2), 175–218.

Christodoulou, A., & Osborne, J. F. (2014). The science classroom as a site of epistemic talk: A case study of a teachers' attempts to teach science based on argument. Journal of Research in Science Teaching, 51(10), 1275–1300.

Cornelius, L. L., & Herrenkohl, L. R. (2004). Power in the classroom: How the classroom environment shapes students' relationships with each other and with concepts. Cognition and Instruction, 22(4), 467–498.

DeBarger, A. H., Choppin, J., Beauvineau, Y., & Moorthy, S. (2013). Designing for productive adaptations of curriculum interventions. In B. J. Fishman, W. R. Penuel, A. -R. Allen, & B. H. Cheng (Eds.), National society for the study of education yearbook: Design based implementation research (pp. 298–319). New York, NY: Teachers College Record.

DeBoer, G. E. (1991). A history of ideas in science education: Implications for practice. New York, NY: Teachers College Press.

Duschl, R. A. (1990). Restructuring science education: The importance of theories and their development. New York, NY: Teachers College Press.

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

Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, values, and goals. Annual Review of Psychology, 53(1), 109–132. doi: 10.1146/annurev.psych.53.100901.135153

Edelson, D. C. (2001). Learning-for-use: A framework for integrating content and process learning in the design of inquiry activities. Journal of Research in Science Teaching, 38(3), 355–385.

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

Erduran, S., Simon, S., & Osborne, J. F. (2004). Tapping into argumentation: Developments in the application of toulmin's argument pattern for studying science discourse. Science Education, 88, 915–933.

Ford, M. J. (2008). 'Grasp of practice' as a reasoning resource for inquiry and nature of science understanding. Science & Education, 17(2–3), 147–177. doi: 10.1007/s11191-006-9045-7

Ford, M. J. (2012). A dialogic account of sense-making in scientific argumentation and reasoning. Cognition and Instruction, 30(3), 207–245. doi: 10.1080/07370008.2012.689383

Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. Review of Research in Education, 30, 1–32.

Forte, A., & Bruckman, A. S. (2009). Writing, citing, and participatory media: Wikis as learning environments in the high school classroom. International Journal of Learning and Media, 1(4), 23–44. doi: 10.1162/ijlm_a_00033

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

Giere, R. N., Bickle, J., & Maudlin, R. F. (2006). Understanding scientific reasoning. 5th ed. Belmont, CA: Thomson/Wadsworth.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. Journal of Research in Science Teaching, 28(9), 799–822. doi: 10.1002/tea.3660280907

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

Henry, J., Breuilly, J., & Porter, R. (1997). The scientific revolution and the origins of modern science. Basingstoke: Macmillan.

Herrenkohl, L. R., & Guerra, M. R. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. Cognition and Instruction, 16(4), 431–473.

Herrenkohl, L. R., Palincsar, A. S., DeWater, L. S., & Kawasaki, K. (1999). Developing scientific communities in classrooms: A sociocognitive approach. Journal of the Learning Sciences, 8(3–4), 451–493.

Hogan, K., & Corey, C. (2001). Viewing classrooms as cultural contexts for fostering scientific literacy. Anthropology & Education Quarterly, 32(2), 214–243.

Hutchison, P., & Hammer, D. (2009). Attending to student epistemological framing in a science classroom. Science Education, 94(3), 506–524. doi: 10.1002/sce.20373

Jimenenez-Aleixandre, M. P., Rodriguez, A. B., & Duschl, R. A. (2000). "Doing the lesson" or "doing science": Argument in high school genetics. Science Education, 84(3), 757–792.

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. Science Education, 94(3), 525–551.

Kapur, M., & Bielaczyc, K. (2012). Designing for productive failure. Journal of the Learning Sciences, 21(1), 45–83.

Kenyon, L., Schwarz, C. V., & Hug, B. (2008). The benefits of scientific modeling. Science and Children, 46(2), 40–44.

Kitcher, P. (1989). Explanatory unification and the causal structure of the world. In P. Kitcher, & W. Salmon (Eds.), Scientific explanation (pp. 410–505). Minneapolis, MN: University of Minnesota Press.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design into practice. The Journal of the Learning Sciences, 12(4), 495–547.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. Science Education, 92(1), 1–32.

Krajcik, J., Reiser, B. J., Sutherland, L. M., & Fortus, D. (2013). Investigating and questioning our world through science and technology (IQWST). 2nd ed. Greenwich, CT: Sangari Active Science.

Kuhn, D., & Pease, M. (2008). What needs to develop in the development of inquiry skills? Cognition and Instruction, 26(4), 512–559. doi: 10.1080/07370000802391745

Langer, J. A., & Applebee, A. N. (1986). Reading and Writing Instruction: Toward a Theory of Teaching and Learning. Review of Research in Education, 13, 171. http://doi.org/10.2307/1167222

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), Handbook of research on science education (pp. 831–879). Mahwah, NJ: Lawrence Erlbaum Associates.

Lee, C. D. (2006). "Every good-bye ain"t gone': analyzing the cultural underpinnings of classroom talk. International Journal of Qualitative Studies in Education, 19(3), 305–327. http://doi.org/10.1080/09518390600696729

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy: Supporting development in learning in contexts. In W. Damon, R. M. Lerner, K. A. Renninger, & I. E. Sigel (Eds.), Handbook of child psychology, 6th ed. (Vol. 4, pp. 153–196). Hoboken, NJ: John Wiley and Sons.

Lemke, J. L. (1990). Talking science: Language, learning, and values. Norwood, N.J.: Ablex.

Lewis, C. T., & Belanger, C. (2015). The generality of scientific models: A measure theoretic approach. Synthese, 192, 269–285. doi: 10.1007/s11229-014-0567-2

Louca, L., Elby, A., Hammer, D., & Kagey, T. (2004). Epistemological resources: Applying a new epistemological framework to science instruction. Educational Psychologist, 39(1), 57–68.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. Science Education, 96(6), 1071–1105. doi: 10.1002/sce.21030

Manz, E. (2014). Representing student argumentation as functionally emergent from scientific activity. Review of Educational Research. doi: 10.3102/0034654314558490

Mason, J. (1989). Mathematical abstraction as the result of a delicate shift of attention. For the Learning of Mathematics, 9(2), 2–8.

McNeill, K. L. (2009). Teachers' use of curriculum to support students in writing scientific arguments to explain phenomena. Science Education, 93(2), 233–268. http://doi.org/10.1002/sce.20294

McNeill, K. L., & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. Journal of Research In Science Teaching, 45(1), 53–78.

McNeill, K. L., & Krajcik, J. (2009). Synergy between teacher practices and curricular scaffolds to support students in using domain-specific and domain-general knowledge in writing arguments to explain phenomena. Journal of the Learning Sciences, 18, 416–460.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. The Journal of the Learning Sciences, 15(2), 153–191.

McNeill, K. L., & Pimentel, D. S. (2010). Scientific discourse in three urban classrooms: The role of the teacher in engaging high school students in argumentation. Science Education, 94(2), 203–229.

Mcneill, K. L., & Vaughn, M. H. (2010). Urban high school students' critical science agency: Conceptual understandings and environmental actions around climate change. Research in Science Education, 42(2), 373–399.

Mehan, H. (1979). Learning lessons: Social organization in the classroom. Cambridge, MA: Harvard University Press.

Moje, E. B., Peek-Brown, D., Sutherland, L. M., Marx, R., Blumenfeld, P., & Krajcik, J. (2004). Explaining explanations: Developing scientific literacy in middle-school project-based science reforms. In D. Strickland & D. E. Alvermann (Eds.), Bridging the gap: Improving literacy learning for preadolescent and adolescent learners in grades 4–12 (pp. 227–251). New York: Teachers College Press.

Morgan, W., & Beaumont, G. (2003). A dialogic approach to argumentation: Using a chat room to develop early adolescent students' argumentative writing. Journal of Adolescent and Adult Literacy, 47(2), 146–157.

National Research Council. (2007). Taking science to school: Learning and teaching science in grades K-8. Washington, DC: National Academies Press.

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

Nersessian, N. (2002). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal (Eds.), The cognitive basis of science (pp. 133–153). Cambridge: Cambridge University Press.

NGSS Lead States. (2013). Next Generation Science Standards: For states, by states. Washington, DC: The National Academies Press.

Osborne, J. F. (2014). Teaching scientific practices: Meeting the challenge of change. Journal of Science Teacher Education, 25(2), 177–196.

Osborne, J. F., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. A. (2003). What "ideas-about-science" should be taught in school science? A delphi study of the expert community. Journal of Research in Science Teaching, 40(7), 692–720.

Osborne, J. F., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. Journal of Research in Science Teaching, 41(10), 994–1020.

Paretti, M. (2009). When the teacher is the audience: Assignment design and assessment in the absence of “real“ readers. In M. Weiser, B. Fehler, & A. Gonzalez (Eds.), Engaging audience: Writing in an age of new literacies. Urbana, IL: National Council of Teachers of English.

Passmore, C. M., Gouvea, J. S., & Giere, R. (2014). Models in science and in learning science: Focusing scientific practice on sense-making. In M. R. Matthews (Ed.), International handbook of research in history, philosophy and science teaching (pp. 1171-1202). Netherlands: Springer.

Passmore, C. M., & Svoboda, J. (2012). Exploring opportunities for argumentation in modelling classrooms. International Journal of Science Education, 34(10), 1535–1554. doi: 10.1080/09500693.2011.577842

Petraglia, J. (1995). Spinning like a kite: A closer look at the pseudotransactional function of writing. Journal of Advanced Composition 15(1), 19–33.

Pluta, W. J., Chinn, C. A., & Duncan, R. G. (2011). Learners’ epistemic criteria for good scientific models. Journal of Research in Science Teaching, 48(5), 486–511. doi: 10.1002/tea.20415

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. The Journal of the Learning Sciences, 13(3), 273–304.

Reiser, B. J., & Tabak, I. (2014). Scaffolding. In R. K. Sawyer (Ed.), The Cambridge handbook of the learning sciences: Second edition (pp. 44–62). New York, NY: Cambridge University Press.

Roeser, R. W., Midgley, C., & Urdan, T. C. (1996). Perceptions of the school psychological environment and early adolescents’ psychological and behavioral functioning in school: The mediating role of goals and belonging. Journal of educational psychology, 88(3), 408.

Rosebery, A. S., Warren, B., & Conant, F. R. (1992). Appropriating scientific discourse: Findings from language minority classrooms. Journal of the Learning Sciences, 2, 61–94.

Russ, R. S. (2014). Epistemology of science vs. Epistemology for science. Science Education, 98(3), 388–396. doi: 10.1002/sce.21106

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. Science Education, 92(3), 499–525.

Sampson, V., Grooms, J., & Walker, J. P. (2010). Argument-driven inquiry as a way to help students learn how to participate in scientific argumentation and craft written arguments: An exploratory study. Science Education, 95(2), 217–257. doi: 10.1002/sce.20421

Sandoval, W. A. (2005). Understanding students’ practical epistemologies and their influence on learning through inquiry. Science Education, 89(4), 634–656.

Sandoval, W. A. (2014). Science education’s need for a theory of epistemological development. Science Education, 98(3), 383–387. doi: 10.1002/sce.21107

Sandoval, W. A., & Morrison, K. (2003). High school students’ ideas about theories and theory change after a biological inquiry unit. Journal of Research in Science Teaching, 40(4), 369–392.

Sandoval, W. A., & Reiser, B. J. (2004). Explanation-driven inquiry: Integrating conceptual and epistemic scaffolds for scientific inquiry. Science Education, 88(3), 345–372.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In R. K. Sawyer (Ed.), The Cambridge Handbook of the Learning Sciences (pp. 97–115). Cambridge: Cambridge Univ. Press.

Schaffer, D. W., & Resnick, M. (1999). Thick authenticity: New media and authentic learning. Journal of Interactive Learning Research, 10(2), 195–215. doi: citeulike-article-id:3050512

Schneider, R. M., Krajcik, J. S., & Blumenfeld, P. C. (2005). Enacting reform-based science materials: The range of teacher enactments in reform classrooms. Journal of Research in Science Teaching, 42(3), 283–312.

Schwarz, C. V., Akcaoglu, M., Ke, L., Zhan, L. (2013, April). Fifth grade students’ engagement in modeling practice across content areas: What epistemologies in practice change over time and how? Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Schwarz, C. V., Reiser, B. J., Acher, A., Kenyon, L., & Fortus, D. (2012). MoDeLS: Challenges in defining a learning progression for scientific modeling. In A. C. Alonzo & A. Gotwals (Eds.), Learning progressions in science: Current challenges and future directions (pp. 101–137). Rotterdam: Sense Publishers.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., & Krajcik, J. S. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. Journal of Research in Science Teaching, 46(6), 632–654. doi: 10.1002/tea.20311

Schwarz, C. V., & White, B. Y. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. Cognition and Instruction, 23(2), 165–205.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. Cognition and Instruction, 18, 349–422.

Songer, N. B., & Gotwals, A. W. (2012). Guiding explanation construction by children at the entry points of learning progressions. Journal of Research in Science Teaching, 49(2), 141–165.

Stewart, J., Cartier, J. L., & Passmore, C. M. (2005). Developing underst and ing through model-based inquiry. In M. S. Donovan & J. D. Bransford (Eds.), How students learn (pp. 515–565). Washington, DC: National Research Council.

Strevens, M. (2008). Depth: An account of scientific explanation. Cambridge, MA: Harvard University Press.

Tindale, C. W. (1999). Acts of arguing: A rhetorical model of argument. Albany: State University of New York Press.

Vedder-Weiss, D., & Fortus, D. (2011). Adolescents' declining motivation to learn science: Inevitable or not? Journal of Research in Science Teaching, 48(2), 199–216.

Vedder-Weiss, D., & Fortus, D. (2012). Adolescents' declining motivation to learn science: A follow-up study. Journal of Research in Science Teaching, 49(9), 1057–1095. doi: 10.1002/tea.21049

Vedder-Weiss, D., & Fortus, D. (2013). School, teacher, peers, and parents' goals emphases and adolescents' motivation to learn science in and out of school. Journal of Research in Science Teaching, 50(8), 952–988. doi: 10.1002/tea.21103

von Aufschnaiter, C., Erduran, S., Osborne, J. F., & Simon, S. (2008). Arguing to learn and learning to argue: Case studies of how students argumentation relates to their scientific knowledge. Journal of Research in Science Teaching, 45(1), 101–131.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A. S., & Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. Journal of Research in Science Teaching, 38(5), 529–552.

Wilensky, U. (1999). Netlogo [Computer Program]: Center for connected learning and computer-based modeling. Northwestern University, Evanston, IL. Retrieved from http://ccl.northwestern.edu/netlogo/

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. Science Education, 92(5), 941–967.