Disciplinary Authority and Accountability in Scientific Practice and Learning

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Received 27 March 2007; revised 21 November 2007; accepted 10 December 2007

DOI 10.1002/sce.20263

ABSTRACT: This article explores the relation between how scientific knowledge is created and the reasoning involved in learning content with understanding. Although an asserted parallel between these underpins reform, little is actually known about this relation. This article offers a model of this relation that draws coherent connections between the science studies literature, which suggests ways of conceiving how scientific knowledge is created; and sociocultural learning theory, which suggests ways of conceiving scientific reasoning. This model highlights a dialectic between *construction* and *critique* of claims in both scientific reasoning and practice. A "grasp" of scientific practice as such is instrumental to learning because informational content of scientific knowledge lies not only on the level of facts, but also on the levels of methods and values, and coordinating information across these levels is crucial for understanding. In contrast to prevailing constructivist ideas that highlight student *authority* to construct knowledge as scientists do, this model emphasizes the importance of knowing how to hold claims *accountable*. Thus, the ideal vision of students making *their own sense* of content is superceded by a more defensible ideal vision of students learning how to make *scientific sense* of content. © 2008 Wiley Periodicals, Inc. *Sci Ed* **92:**404–423, 2008

INTRODUCTION

A proper understanding of a scientific idea requires that one also know something about the architecture of that knowledge—that is, how it is constructed. Students generally do not understand scientific ideas when they are merely committed to memory. As a result, reform efforts have been developing ways to instill the process of learning science with some authenticity, the basic idea being that the learning process should in some ways parallel the process by which scientists construct knowledge (National Research Council, 1996). Rather than passively submitting to the authority of teacher or text, students should, like the scientist, actively make their own sense of nature.

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This parallel between the learning process and scientific practice has been intuitively compelling at least since Schwab theorized on the "structure of disciplines" (Schwab, 1962) and perhaps since Dewey wrote about the "nature of subject matter" (Dewey, 1916). Subsequent scholarship has worked out in some detail what it might mean to construct ideas as scientists do.[1] However, this general approach has not been without critics. Some scholars, many of them with a philosophical or strong disciplinary background, have objected that students neither can nor should be given the authority to construct scientific ideas on their own (e.g., Niaz et al., 2003; Nola, 1997; Nola & Irzik, 2006; Matthews, 1998).

Although it may be tempting to categorize these objections as educationally naïve, misdirected, or applying only to extreme constructivist positions (e.g., von Glasersfeld, 1995), there is nevertheless a genuine problem with the notion that learning should parallel scientific construction of knowledge. The problem manifests itself as both relativism and a pedagogical dilemma. In terms of relativism, if students have authority to construct their own knowledge, the scientific account is no longer authoritative. Some science educators have lamented this problem in terms of "viability replacing validity" in constructivist classrooms (e.g., Abd-El-Khalick & Akerson, 2006; Osborne, 1996). Pedagogically, teachers face a choice of whether to allow students to make their own sense of nature, and risk getting it wrong, or to didactically explain the scientific account, thereby precluding student authority and perhaps understanding (Windschitl, 2002). Interestingly, this pedagogical dilemma also has been noted in mathematics education (e.g., Lampert, 1985; Ball & Bass, 2000) and related to problems with constructivism more broadly (Phillips, 1995).

The thesis of this article is that these problems reflect an overemphasis on the *construction* of knowledge (a la constructivism) and *authority* being provided students to do so without sufficient attention to *critique* of claims and *accountability*, in particular how these are intertwined in scientific practice and reasoning. It is clearly important for students to understand something about the architecture of scientific knowledge. In science as a social practice, critique motivates authentic construction of knowledge that is uniquely scientific. Similarly in individual learning, authentic construction of knowledge may not be possible without a grasp of disciplinary critique. This vision offers a way to avoid constructivist problems. Students need not recapitulate in the learning process what scientists have done to construct knowledge. But a grasp of scientific practice, its key reasoning patterns, and an awareness of the architecture of knowledge these produce can be crucial resources in learning novel scientific ideas with understanding.

This theoretical argument is presented here in three parts, highlighting clear connections between scientific practice, scientific reasoning, and genuinely understanding content. The first two parts focus on the relation between scientific practice and scientific reasoning. From science studies literature, it draws a vision of how scientific practice works, in particular by showing how the authority for new knowledge claims grounds out. The basis of this authority is at once both social and material, and in a very particular way, not arbitrary. From this picture of scientific practice, I will then draw inferences about the reasoning patterns scientists must engage to achieve authority for their knowledge claims. These reasoning patterns, general to science across domains, reflect an interplay between construction (e.g., presenting at conferences and authoring articles) and critique (e.g., reviewing proposals and manuscripts). Through participation in practice, scientists come to *know that* scientific knowledge is held accountable by explicit connections to nature, to *know how* to play the roles of constructor and critiquer appropriately, and to *know that* the interaction of these roles in practice yields reliable knowledge.

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[1] The conceptual change model (Hewson, Beeth, & Thorley, 1998; Posner, Strike, Hewson, & Gertzog, 1982) is perhaps the most thoroughly developed example of this kind of scholarship.

The third part of my argument is that a general “grasp” of scientific practice as such may be central for learning novel content. A grasp of practice is necessary for scientists to participate in the creation of new knowledge because it provides an overview of its architecture and how to navigate it. A grasp of practice motivates and guides a search within this architecture for the informational content, indeed the meaning, of canonical scientific knowledge. Scientists tend to understand scientific claims as assertions to be problematized through scrutiny of data. Students, to understand scientific ideas that are new to them, need do the same. Rather than being left to make their own sense of scientific content as they choose, students should be taught to make *appropriate* sense. For students to do this, they need to know what scientists know, in general, about science.

My purpose here is merely to make plausible this substantial revision in the way we think about the relation between scientific practice, scientific reasoning, and learning of novel content. Conceiving of the connections across these in terms of knowledge construction has helped us move beyond a notion of science learning as committing facts to memory. Considering the social and psychological dialectic between construction and critique across these offers an opportunity to reexamine not only the theoretical and pedagogical problems of constructivism, but may prove a fruitful framework for curricula and pedagogy. Students cannot come to know all scientific ideas as scientists originally came to know them, but students can and should *understand* these ideas as scientists *understand* them.

GROUNDING OF SCIENTIFIC AUTHORITY IN PRACTICE

According to a popular view, the basis of authority in science resides in the effective constructive reasoning of the individual. This reasoning is considered logically sound, and investigations result from this reasoning in which the methods effectively create new knowledge. This view has a longstanding history both philosophically and educationally. Philosophically, it is related to a framework broadly referred to as the “positivist endeavor” (e.g., Comte & Martineau, 1853; Popper, 1968), which casts the success of science in terms of universal logic and scientific methods. Educationally, providing students access to authority in science involves provision in some way of these sound-reasoning patterns. The notion of teaching “scientific method” stems from this vision, as do research programs that provide students with other constructive reasoning patterns, be these characterized for example as the logic of controlling variables (Toth, Klahr, & Chen, 2000) or an argument template consisting of claims, evidence, warrants, backings, and rebuttals (Erduran, Simon, & Osborne, 2004).

This section briefly summarizes recent science studies scholarship that draws this vision into question. In terms of how individuals reason in science, this scholarship suggests that critique reasoning, in addition to constructive reasoning, is key to achieving authority in science. To understand how this is so, we will need to turn our attention briefly away from the level of individual reasoning to the level of the community practices.

A growing body of work in science studies asserts that disciplinary authority in science is social. That is, rather than its basis being in what an individual can do alone, it rests in the community of scientific peers. Members of this community work in a particular area and make decisions regarding what counts as a new knowledge claim. Individuals can achieve authority, that is, convince peers to accept a new knowledge claim, by demonstrating a conformity between that claim and the behavior of nature. The process by which this authority is achieved involves a dialectic between the individual scientist who works to construct a case for a new knowledge claim and the community that critiques the case. The process is driven by identification of potential errors in the inferential chain of evidence offered for the claim and iterative removal of those errors in practice (Mayo, 1996; Rouse, 1996). In this process, the reasoning that is fundamental to achieving authority is not, as in the positivist version, primarily about construction, but a dialectic of construction and critique—success occurs when the individual scientist learns to anticipate the community critiques on the new knowledge claim.

In science studies literature, the focus on the social nature of authority was brought to the fore in a sociological stream of scholarship. The sociology of scientific knowledge (or SSK,[2] as Pickering, 1995, refers to it) grew primarily in reaction to the hegemony of the positivist vision. SSK reacted to the notion that science deserves a privileged status as "objective," where objectivity is a feature of individual reasoning. From empirical studies of scientific practice, it became clear that scientists are not always objective, logical reasoners, but are subjective as well, influenced by political, career, and other social concerns, and sometimes these concerns play into the scientific arguments themselves. An extreme version of the focus on social factors in scientific practice posits that social factors actually *determine* scientific decisions, a version aptly named the "strong program" (Barnes & Bloor, 1982).

The contribution of SSK was to show that the positivist vision of scientists as purely objective reasoners is false. SSK effectively substituted logical reasoning with social power as the basis of authority in science, a substitute that was problematic and controversial. Social power can mean the imposition of one view over others using political, economic, or other nonrational pressures. Under this vision, it became unclear whether and how science is different from other forms of social competition. If the basis of authority in science is simply to grab positions of leadership in the community from which power could be wielded, then science did not deserve its status as rational or privileged. The controversies around SSK thus involved not only an epistemological problem, but also the status of science as an institution in society.

Important to our purposes is the epistemological problem. The fact of the matter is, over several hundred years science has resulted in considerably reliable knowledge claims. The positivist version of science had an explanation for this, and whereas SSK showed that explanation to be unworkable, it did not provide an alternative explanation in its place. It seemed improbable that a basis of authority in social power could be responsible for the effectiveness of science in accessing the underlying structures in nature. This especially because since its inception, scientific rationality was considered in contrast to reasoning based in tradition, ideology, and superstition (Toulmin, 1990).

In sum, SSK succeeded in shifting the locus of disciplinary authority from the individual scientist to the community by asserting that the social level of human interactions is relevant to how "what counts" as new knowledge gets decided. However, it did not provide a satisfactory epistemological account of *how* this gets decided. Individually, scientists engage in debate and compete against each other, whereas on the communal level, science is a collaborative effort. As a community, how do scientists decide which knowledge claims should be accepted and which should not?

Several science studies scholars have noted that the vision of scientists debating to decide the source of authority is incomplete, and the missing part is a scheme of accountability for claims. As Pera (1994) noted, there are not just competing scientists present in the debate, but also a crucial third party—nature herself. In science, claims are accountable to the way nature actually behaves. Nature is what it is, despite our ideas about it. So because the aim

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[2] See Pickering (1995, chapter 1) for an accessible summary of the history, strengths, and weaknesses of SSK. SSK is related philosophically to pragmatism and educationally to socialconstructivist learning theory. See Garrison (1997) for a well-developed position for science education highlighting these connections and Davson-Galle (2000) for a critique of it.

of science is to explain nature, and because nature is indifferent to our beliefs about it, nature is the final arbiter of debates in science (Pera, 1994; Rouse, 1996).

At first, this seems simple enough, but in practice the picture is more complicated. Whereas it is clear that nature provides a crucial "voice" arbitrating debates between scientists and their rival explanations, it would be a mistake to locate the basis of authority in science with nature, as a naïve empiricism would have it. This is because nature does not simply show up "at the table" of debate (Pera, 1994), but must be brought there. It is not nature unproblematically observed, but the way nature's behavior is portrayed and related to new knowledge claims that gives her an arbitrating role, and scientists work to marshal her to their side. This does mean that "data are theory-laden" (Duhem, 1969; Hanson, 1958), because the ways scientists frame, measure, and represent nature are directly related to the theoretical notions they are asserting. However, this does not mean that we can make whatever we want of nature's behavior (Pera, 1994). To express the extent to which nature acts as a constraint on ideas, some philosophers have argued it is best to think of nature as exerting "material agency" in scientific debates (Pickering, 1995). In this way, the material aspects of practice, the work that comprises most of scientists' efforts, is the work that is ultimately responsible for achieving authority in science (Hacking, 1983; Pickering, 1995; Rouse, 1987, 1996).

There are two interrelated senses of material practice. In one sense, scientists probe nature by manipulating material to focus on aspects of it and isolate these from others.[3] For example, although we are familiar with gravity and may even notice free fall in everyday observations, we cannot simply see the patterns of speed change during free fall. Identifying these patterns requires more than bearing witness to falling objects. To distinguish between everyday seeing and scientific observations, Hacking (1983) introduces a particular meaning for *phenomenon.* A phenomenon is both natural and unnatural; it is nature's behavior but behavior cornered and gripped by particular material arrangements the scientist creates. Thus Hacking says, to be *observed* in a scientific sense, a phenomenon must be *created.* In this way, his use of "phenomenon" is different from the colloquial use of the term. Scientists create phenomena so particular aspects of nature become isolated, framed, and related to some sort of systematic scale to serve as an arbiter for a knowledge claim.

The second sense of material practice is the work involved in making nature's behavior apparent for peers to support arguments about theory (Goodwin, 1994; Latour, 1990). Whereas the first aspect of material practice is more about what the scientists do to get nature to "speak," the second aspect is more about the way nature's "voice" gets portrayed, to convince the peer community of the existence of a pattern in nature. Laboratory results alone do not result in scientific claims. These results must become part of a rhetorical effort that involves specific details about what the scientist did and how nature responded (see Bazerman, 1988, for a detailed history of this rhetorical form). Although now rhetorically framed rather than just observed, the crux of arguments is still the "explicit connection" to nature's behavior (Rouse, 1996).

Thus, although authority for deciding upon knowledge claims in science lies in the community, decisions are not arbitrary, but depend on how successful scientists are in demonstrating a clear conformity between the knowledge claim and the behavior of nature, within the accepted rhetorical form. Scientists construct phenomena and data, and their peers critique these constructions in terms of how well they shed light on nature's underlying

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[3] Manipulation per se is not a part of all sciences, of course. In astronomy, for example, scientists do not manipulate celestial objects. But they do frame observations in ways that produce unique "phenomena" that are dissimilar in kind to everyday observations. Major advances have been accompanied by this distinction in modern astronomy—that is, since the telescope.

structure. In this way, authority is achieved through constructions being held accountable to the way nature actually is.

With this vision of how authority is grounded in the architecture of scientific knowledge, we can now turn to how this is achieved in practice. How do explicit connections that demonstrate conformity between knowledge claims and nature get constructed, and what can we infer about the individual scientists' reasoning in this process?

AUTHORITY AND ACCOUNTABILITY THROUGH CONSTRUCTION AND CRITIQUE

The construction of explicit connections to nature's behavior is fundamentally a communal effort. This is not to say that all scientists in the community are simultaneously trying to construct a particular knowledge claim. On the contrary, whereas each individual scientist is trying to construct his or her own explicit connection to nature's behavior, his or her peers are trying to find errors with it, that is, to critique the knowledge claim and its explicit connection to nature's behavior. This mechanism of peer review, familiar to us all, takes on a new importance in this section. Recent science studies scholars argue that the relative reliability of scientific claims and indeed rationality itself can be explained through these culturally based, discipline-specific patterns of interaction. As such, an explanation for science lies not on the level of individual reasoning, but on the level of communal function. This does not render the reasoning of individual scientists irrelevant, neither to science's effectiveness nor to our educational concerns. But this analysis of scientific practice does suggest that individual reasoning is not exclusively a constructive matter, but a dialectic of reasoning through both construction and critique of knowledge claims. Indeed, the emphasis on critique reasoning and accountability may be considerably more important than historically acknowledged, both for explaining how scientists think and for understanding what our students need to know about science to learn with understanding.

Construction of scientific knowledge is first of all public, a collaborative effort among a community of peers working in a particular area. "Collaborative" may seem a misnomer because individual scientists compete with each other in their debates about new knowledge claims. Yet this sense of collaboration is important: it checks individual scientists from being given authority for new knowledge claims prematurely.

When scientists present arguments for a new knowledge claim, their peers seek errors in the inferential chain that forms the "explicit connection" to nature's behavior, or the architecture of that claim. The way a phenomenon is framed may not align with the new knowledge claim. The way it was isolated may contain confounds in nature's behavior such that the pattern identified is not caused by the factor posited. The way measurements are made may not result in numbers that reflect natures' behavior. And the way data are represented may mislead rather than reveal. Peers are particularly effective at identifying such errors for at least two reasons. First, they have an individual interest in finding errors because they are typically in competition with the scientist who put forward the claim. Second, peers often have worked for some time in the same conceptual and material space. They have faced some of the same problems and have weighed options, and therefore are intimately familiar with the tedious details involved in the presented knowledge claim and its chain of evidence. It is hard to imagine anyone better suited to identify errors in a scientific argument than a scientist's peers.

Rather than inhibiting the aim of the presenting scientist, however, this identification of errors actually helps. As Mayo (1996) noted, a key feature of science and possibly its central strength is the institutionalized removal of errors. Feedback from peers contains information that points to particular ways the knowledge claim and its explicit connection to nature could be strengthened, and the scientist uses this to return to the laboratory (or field) and revise. In an iterative process, the scientist returns to the public forum again and the knowledge claim is given scrutiny. This is repeated until the peer community can find no errors in the scientists' demonstration of an explicit connection with nature's behavior.

Notice also that this characterization of scientific practice has an explanation for the relative reliability of scientific knowledge. Whereas the positivist approach locates an explanation for rationality on the individual level, this characterization of scientific practice explains rationality on the communal level. That is, individual scientist reasoning, subjective motivations, and actions being what they are, on the communal level there are mechanisms through which individual ideas become scientific knowledge. Individuals do not produce scientific knowledge—communities do (Longino, 2002).

Does a communal explanation of rationality imply that the way individual scientists reason is irrelevant? Not at all. Although rationality is not an exclusively cognitive matter, the way scientists interact on the communal level is of course related to particular reasoning patterns. Scientists can be more or less successful in achieving authority for their knowledge claims within this vision of communal practice, and their success rests on their ability to reason well. However, we see that sound construction of knowledge claims does not sufficiently characterize the reasoning that is important, as in the positivist model. Scientists who are successful are so because they learn how to *critique* their own knowledge claims as their peers do. In contrast to the positivist vision, a dialectic of *construction and critique* characterizes scientific reasoning involved in generating new knowledge claims. Construction without appropriate critique would not result in science.

GRASP OF PRACTICE AND SCIENTIFIC REASONING

If we consider that successful scientists are those who effectively engage in this dialectic of construction and critique, we can begin to see what it is that students require to understand scientific content. If construction without appropriate critique would not result in the creation of new scientific knowledge, it may be the case that in terms of learning, constructing a genuine understanding of old scientific knowledge requires an awareness of the rationale and nature of critique in scientific practice. Before turning to this point, the present section will elaborate on the features of individual reasoning that are key to successful participation in scientific practice.

Scientific reasoning always has both context-specific and general aspects. Recent history of research on scientific reasoning reflects a debate about the relative importance of each. On the one hand, general theories of scientific reasoning hold promise for their power to support student abilities in a variety of contexts. Several general characterizations include coordination between theory and evidence (e.g., Kuhn, 1993), argumentation templates (e.g., Toulmin, 1958), and the control of variables strategy (Chen & Klahr, 1999). On the other hand, reasoning is always reasoning "about" something (Lehrer & Schauble, 2006). There are solid arguments that assert domain knowledge, rather than any general reasoning template, is key to reasoning scientifically in a domain (e.g., Koslowski, 1996; Rudolph, 2000; Schauble, 1996). Yet the sense remains that something general about scientific reasoning, something that crosses domain boundaries, is both part of what scientists know and potentially important for education.

The general formulation of scientific reasoning presented here offers a novel and potentially far-reaching relationship between its domain-specific and general aspects. Rather than a formulation exclusively in terms of constructive templates like logic or argumentation, this formulation includes the reasoning of critique. Moreover, although expressed explicitly here, this account of scientific reasoning includes knowledge that is implicitly known by scientists. As the analysis of practice above suggests, in their work scientists consciously focus on nitty-gritty details in their domain of expertise, both when they are constructing data and claims and when critiquing them. Nevertheless, scientists know in a more implicit sense, how to act appropriately, to participate in practice (Lave & Wenger, 1991). The idea that knowledge necessary for participation is implicit is not surprising if we view science as a culture and acknowledge that much of what people know culturally is implicit (Rogoff, 2003). The key point for us is that such knowledge, or what I call a "grasp of practice," may enable learning about a novel content, even in a new domain area. This conjecture suggests that scientists are better prepared to learn novel scientific content with understanding than laypeople. It also suggests what students need to know to "make sense" of novel scientific content in ways that reflect both disciplinary authority and accountability.

This section elaborates key components of a grasp of practice and describes some empirical support for them. Before turning to how a grasp of practice might influence learning of scientific content, below I briefly summarize evidence for a grasp of practice in research on a closely related area: students learning how to generate new scientific knowledge.

Grasp of Practice and Creating New Scientific Knowledge

Theoretically. A grasp of practice is the result of what scientists learn from extended participation in scientific practice. The seeming circularity of this definition reflects its connection to sociocultural learning theory. Sociocultural learning theory, in contrast to cognitive and behaviorist theories, historically has focused less on "what" is learned than on "how" it is learned (Papert, 2006). "What" is learned has been left rather vague, expressed, for example, as participation (Lave & Wenger, 1991) or internalization of cultural practices (Vygotsky, 1978) or enculturation (Rogoff, 2003).

Nevertheless, we can use what we know about scientific practice to infer several things scientists must know, implicitly and/or explicitly, in order to participate in it. First, scientists *know that* scientific knowledge is held accountable through its explicit connections to nature's behavior. Second, scientists *know how* to play the roles of constructor and critiquer appropriately, a component of both, as noted above, is how to scrutinize the explicit connections demonstrated between a claim and nature's behavior in data. Third, scientists *know that* the interaction of these on the communal level produces reliable scientific knowledge. This list of what scientists must know to participate in practice (see Ford & Forman, 2006, for a more elaborate argument about this) can be considered a modest explication of "what" scientists learn, through sociocultural learning mechanisms, during their participation in practice.

Empirically. The potential psychological centrality of this sociocultural way of knowing about a community's practice has motivated multiple research projects to explicate it. A particularly thorough example in science education is Engle and Conant (2002). Engle and Conant examined a Fostering Communities of Learners classroom (Brown & Campione, 1996), focusing on one activity and noting the features of instruction that seemed to be related to the "productive disciplinary engagement," or authentic scientific work by the students, apparent in it. From this, they generated four principles for fostering productive disciplinary engagement: problematizing content, giving students authority, holding students accountable to disciplinary norms, and providing appropriate resources. These principles were then noted to be present in other classroom activity designs that were also successful in getting students to engage in authentic scientific work (Hatano & Inagaki, 1991; Rosebery, Warren, & Conant, 1992). Engle has extended this analysis and the appeal to authority and accountability in a more recent study to explain the transfer evident in a classroom event (Engle, 2006).

Ford (2005, in press) also appealed to sociocultural learning mechanisms to design a study in which students learned how to participate in experimentation. This study randomly assigned students to two conditions, one of which engaged students in guided conversations about how to construct an experiment to answer the question, "How does steepness affect speed?" Students tackled this question in small groups, first by formulating experimental designs, then by collecting and analyzing data. Between these phases of the activity, groups reported their strategies and results to the whole class in formal presentations, and the audience was assigned the role to critique them based on what they learned during their own constructive efforts. In this way, the activity design simulated both constructor and critiquer roles and the way they interact around minute details of data collection and analysis in scientific practice.

In an assessment task, students from this class and another (who experienced alternative instruction on experimentation) were asked to conduct experiments to answer a novel question, "If you drop a ball, how does the drop affect the bounce?" Analyses of the performances showed that students who had experienced the interrelated roles of constructor and critiquer in the ramp activity transferred considerably sophisticated aspects of experimentation to the new context. These included standardizing and quantifying variables, running multiple trials, and representing and analyzing results in systematic ways (Ford, 2005).

These performances more recently were subjected to a secondary analysis to test the question of whether students had learned some "scientific method" rather than having been enculturated into key aspects of experimental practice. This analysis showed that student performances developed idiosyncratically in ways that were contingent upon their previous choices. That is, there was not any general methodological template apparent at the outset that got "filled in" with details as they worked, as a positivist vision of scientific reasoning would suggest. In addition, although performances were considerably homogeneous in their rigor, they were also strikingly varied in their domain detail. For example, students did not operationalize the variables in the same ways. Ten pairs of students came up with and studied multiple different ways of characterizing "drops" and "bounces." These aspects of variation in performances seem to be incompatible with the hypothesis that students had learned a method or procedural rules. Rather, their rigorous and varied performances suggest that they had learned generally what the aims of experiments are, that is, to construct a conformity between an account of nature and nature's behavior, and that the way to do this is to take some steps and iteratively revise in response to self-critiques.[4]

The analyses by Engle and Conant (2002), Engle (2006), and Ford (2005, in press) of apparent student engagement in scientific work suggest that a grasp of practice can be learned and that it is somewhat general (evidently supporting transfer to novel contexts). However, these analyses focused on student participation in creating new scientific knowledge. How might a grasp of practice inform how students learn old scientific knowledge?

Grasp of Practice and Learning Old Scientific Knowledge

Theoretically. Recall what scientists must know in order to participate appropriately in scientific practice. First, scientists *know that* scientific knowledge is held accountable through its explicit connections to nature's behavior. Second, scientists *know how* to play

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[4] See Ford (in press) for a detailed argument on this and implications of what students learned in terms of nature of science understanding.

the roles of constructor and critiquer appropriately, which is basically how to scrutinize the explicit connections demonstrated between a claim and nature's behavior in data. Third, scientists *know that* the interaction of these on the communal level produces reliable scientific knowledge.

To apply this grasp of practice to the way scientists learn old scientific knowledge across domains, we need a more nuanced notion of content. For this, I borrow a formulation of scientific content from Laudan (1984). Laudan argued that science is distinguished by its high degree of consensus on its content, and identified three interrelated dimensions of this content: facts, methods, and values. Laudan's purpose was to elaborate on the relationship between these levels, using several historical examples for analysis. The purpose here is to use Laudan's formulation of scientific content to elaborate on what and how students need to learn.

Laudan described the relationship between scientific facts, methods, and values in terms of settling disagreements. Disagreements about matters on one level of content cannot be resolved on that level but must appeal to another. Disagreements about matters of fact appeal to methods, and disagreements about matters of method appeal to values. (Laudan uses the word "values" not to represent a sort of scientific morality but rather the notion that methods are judged by how well they achieve the aim of science. So, we might consider "aims" an alternative term to capture this.) Disagreements about values or aims, Laudan argues, distinguish matters of science from matters of nonscience. Coherence on the level of values or aims is, therefore, ultimately responsible both for the high level of consensus on matters of fact in science and for the demarcation of science from other knowledge-producing endeavors.

Consider what is required to really understand scientific ideas in this light. Facts, methods, and values or aims cohere and in part, the meaning of the former rest upon the latter. Understanding ideas involves not only content about facts, but also content about the corresponding methods and scientific values. Disagreements about matters of fact in other knowledge-producing disciplines can remain differences of opinion (consider historical or literary scholarship, e.g.). Not so in science: the facts that "count" are decided through the explicit connections that can be made to nature's behavior. Matters of fact are held accountable by the methods through which this explicit connection is made. As a result, these facts only make sense *scientifically* in light of their corresponding methods.

This stands in contrast to the more common view of content that is limited to matters of fact. The key point here is that by conceiving of content solely in terms of facts, we may miss something important for learning. As such, the analysis here parallels arguments in mathematics education about expanding our conception of content (Gresalfi & Cobb, 2006).

Consider the relationship between Laudan's characterization of scientific content and what scientists know from participation in practice. Scientists know that informational content is located on the distinct but related dimensions of facts, methods, and values or aims. Because they know the relationship between these dimensions, they also know how to locate this informational content: by scrutinizing explicit connections between ideas and nature. This also endows them with appropriate senses of skepticism and trust regarding scientific claims.

First, scientists *know that* scientific knowledge is held accountable through its explicit connections to nature's behavior. They know, therefore, that the informational content to understand scientific facts is also on the level of methods. The meaning of scientific concepts is determined by the way they are measured (Bridgman, 1936). To understand them otherwise is to misunderstand them.

Second, scientists *know how* to play the roles of constructor and critiquer appropriately. That is, scientists know how to scrutinize explicit connections between ideas and nature's behavior in data, which is precisely what one needs to do to identify the particular meaning of a scientific concept. This would imply that when a scientist encounters a novel scientific concept, he or she would automatically appeal for more information. This information would not be just any information, or a general appeal for a better articulation, but a search for how the concept was operationalized and how this fit into the broader use of that concept in a model or theory. Moreover, because a grasp of practice is a set of cultural understandings, this ability and more interestingly, knowing when it is appropriate to draw on these roles, may be more implicitly known than explicit.

Third, scientists *know that* the interaction of these roles in practice results in reliable scientific knowledge. Scientists know the levels and kinds of skepticism and trust that are appropriate for scientific claims. Most basically, this implies treating new claims differently than old knowledge. Old and settled knowledge is considered reliable. The idea and its connection to nature should not be taken lightly, because peers in that area of expertise have scrutinized it, searched for errors, and found none remaining. Thus, for a scientist, their knowledge and ability of scrutinizing the informational content of a novel claim is accompanied by an appropriate amount of trust. Rather than blind trust, scientists who have a grasp of practice know both the kind of trust and the basis for it. For new claims, scientists have skepticism based on a likelihood of errors being present, given the relatively little scrutiny they have been subjected to.

Anecdotally, this is most apparent in arguments in which linguistic information is ambiguous or when new terms are introduced. To find their meaning, we look at how data were collected and analyzed, how nature was framed and displayed. We do this because we know science works this way and that particular purposes are served by this way of defining linguistic meaning. Facts make sense only in light of the methods, through which explicit connections to nature are made. And this scrupulous, tedious definition beyond an everyday sense of linguistic meaning makes sense only in light of science's values or aims.

In this way, a grasp of practice is both a sort of "map" that highlights the relationships among facts, methods, and values and a set of abilities for reasoning coherently across these dimensions. Thus, it may be key for learning that informational content. Scientists know that new scientific ideas are held accountable by peers through their explicit connections to nature, and because of this they also hold their own sense making accountable to the same when learning content that is new to them.

Empirically. This general vision of what scientists know and how it influences their learning of scientific knowledge may make sense, but is it true? Results of a recent study suggest that these different levels of content are involved in the ways scientists make sense of novel scientific content. Ford and Kniff (2006) presented 10 scientists (graduate students in biology, chemistry, or physics) and 10 nonscientists (non-science college graduates) with three brief articles from popular magazines. Each article asserted a science-related claim and provided a data display as evidence for that claim. Claims involved water quality testing, influenza infection in the home, and strategies for exercising. (Although these artifacts are not reproduced here, Table 1 includes reference information.) Scientists and nonscientists were asked two interview questions: (1) about the level of confidence they had in each of these claims and (2) about the kind of information that would increase their confidence.

The results, summarized in Table 1, show that overall, scientists were less confident in these claims, and that they appealed to how the data were collected and analyzed to evaluate their level of confidence. In contrast, nonscientists had more confidence in these claims and appealed to personal anecdotal experiences that reflected their opinion of the claim (i.e., whether they agreed with it or not). Perhaps most tellingly, almost all scientists consistently

TABLE 1
Results from Ford and Kniff (2006)

	Scientists ($n = 10$)	Nonscientists ($n = 10$)	p Value
Water quality (*Popular Mechanics,* 182(6), 40)			
Confidence in claim?	0	7	<.01*
Question how data collected?	5	0	<.05*
Question repetition of collections?	8	1	<.01*
Question statistical analyses?	9	0	<.001*
Relate to anecdotal experience?	0	3	=.21
Germs at home (*Newsweek,* 145(17), 53)			
Confidence in claim?	0	7	<.01*
Question how data collected?	10	2	<.001*
Question repetition of collections?	8	3	=.069
Question statistical analyses?	7	0	<.01*
Relate to anecdotal experience?	0	6	<.01*
Motivating exercise (*Consumer Reports,* 70(1), 16)			
Confidence in claim?	2	3	=1
Question how data collected?	7	2	=.069
Question repetition of collections?	–	–	–
Question statistical analyses?	5	0	<.05*
Relate to anecdotal experience?	0	5	<.05*

*Statistically significant, Two-tailed Fisher's exact test.

appealed to how the claims were constructed immediately—not in answer to the second interview question about information that would increase their confidence, but in response to the first question, about whether they had confidence in the claim. No nonscientists preempted the second question for any of the three claims.

Although these results may not be surprising, we can glean some insights from them into how scientists learn the informational content in a novel scientific claim. First, the reactions of scientists reflect a disposition to scrutinize the explicit connection of the claim to nature, even if they are not located in a professional setting or the claims are outside their domain of expertise. This means that scientists know what one is supposed to do with a scientific claim (i.e., critique it), and this knowledge is at least somewhat general. Their knowledge seems to have a "just because" quality about it, because scientists were not cued to critique these claims. Rather, scrutinization of critique seems simply what is done with claims. A second important point is that scientists know there is a particular way to critique claims, which is in light of how the data were collected and analyzed. Conversely, the scientist knows the kind of information that would temper the skepticism and lead to greater confidence in or acceptance of the claim. Notice that this information, appealed to for critique, is an understanding of how scientific claims are constructed (or more specifically, how they are *expected to be* constructed) in practice.

The psychological resource scientists draw on in their reactions to science-related claims distinguishes "appropriate" reactions from those of nonscientists. In one sense, this is not surprising. Indeed, those of us who have engaged in scientific practice have surely experienced the role of critiquing a claim, and it is clear that this role involves scrutiny of the claim's construction. Typically, however, we understand this role as limited to a particular area of expertise, and we consider the knowledge involved in critique as specific to the methods and standards of that particular content area. By considering how the reactions of scientists across natural domains appeal to the same notion of critique (and contrast so clearly with the reactions of nonscientists), it seems that the resource is more general than our individual domain-specific experiences suggest. One way to account for this apparently general reaction of scientists is in terms of a grasp of practice. Scientists recognize scientific claims as a part of scientific practice, and know how to react appropriately to them. An appropriate reaction is to scrutinize the way data were collected and analyzed, in essence the explicit connection, along an inferential chain, to nature. Scientists react to knowledge claims seamlessly as critiquers of the claim and its evidence.

Scientists' reactions to these claims are notable most basically for the recognition that occurred. Scientists recognized the claims as *scientific*, different in kind from everyday claims. The scrutiny seems more like the way scientists search for the meaning of those claims. The informational content of scientific claims, unlike everyday claims, is comprised by the explicit connection to nature and what function that connection serves toward the valued aim of the practice more broadly.

Laypeople seem to have less of an understanding of critique reasoning and how this functions in scientific practice. They do not know that the informational content of scientific claims consists of its explicit connection to nature in light of the community's valued aims. They do not react in a scientific way to the claims, but in an everyday way. Therefore, they search for the meaning of the claims by relating them to personal anecdotal experiences. As a result, a nonscientific judgment underlies the confidence laypeople had in these claims. The laypeople wielded authority to decide what counts as knowledge for themselves, but this authority was not tempered by accountability. Unlike the scientists, the laypeople in this study made sense of the novel claims without making scientific sense.

ACCOUNTABILITY AND SCIENTIFIC SENSE MAKING

If we want students to learn the informational content in scientific knowledge, they need to act more like the scientists in this study and less like the laypeople. To act like scientists, they must know what scientists know, in general, about science. They must *know that* scientific knowledge is held accountable through its explicit connections to nature's behavior, *know how* to play the roles of constructor and critiquer appropriately, and *know that* the interaction of these on the communal level produces reliable scientific knowledge, all of which is included in a grasp of practice.

This means students do not need to learn scientific content knowledge in ways that parallel how scientists created it. There is a relationship between the reasoning involved in creating new knowledge and learning old, but there are differences between these that are as important as they are subtle. The accountability scheme for creating new knowledge results in the unique architecture of scientific knowledge, fundamental to which is its nuanced appeal to the behavior of nature through "explicit connections." When knowledge becomes settled and old, these explicit connections define the informational content of that knowledge. Therefore, making scientific sense (as opposed to everyday sense) of these ideas implies holding one's sense making of them accountable to these connections. Scientific sense making is when the informational content of novel ideas (i.e., facts) is identified by scrutinizing their connection to nature (i.e., methods) in light of scientific values, or aims. Understanding the relationships among these dimensions of content is crucial for learning with understanding, and a grasp of practice enables one to do this.

This account of scientific reasoning suggests that grasping the *distinctiveness* of scientific knowledge may be a key aspect of understanding its informational content. Understanding a scientific claim requires a distinct way of holding one's sense making accountable to the relevant methods and values of science. Learning must rest on accountability to the informational content of facts, which stems from how they are held accountable in scientific practice: through methods and resulting data in light of values. Sense making becomes scientific sense making when authority is exercised with the *knowing that* and *knowing how* involved in holding knowledge accountable.

Consider how this account of learning contrasts with a popular constructivist version. Constructivism treats scientific ideas as if they are the same kind of thing as everyday ideas, emphasizing *continuity* between students' everyday ideas and scientific knowledge. Students bring prior knowledge to the classroom, and learning is conceived as relating this everyday knowledge to scientific ideas in much the same way the nonscientists in Ford and Kniff (2006) did. Authority is viewed as freedom to make sense as one wishes. It is authority without accountability in sense making.

This may sound too strong, in particular if we consider the variety of constructivist versions of instruction and the fact that a large part of actual instructional events, in any description of them, remains implicit. Critique is not absent from some instructional forms, in particular some versions of inquiry projects and instruction that focuses on argumentation. But when it is implicit, it remains undefined and its role in supporting learning unclear. If we take theories of learning and instruction seriously, then we must examine what they highlight and why. Constructivism generally highlights student authority, in particular because science learning as commitment of facts to memory remains the norm in too many classrooms. The challenge to constructivism outlined here is not accompanied by advocacy for a transmission theory of instruction and an acquisition theory of learning. Nor should it be taken as a reason to place the authority for knowledge exclusively with the text or teacher. Supplanting the popular lay vision of what it means to learn science requires a clear and rigorous theory. To advance an agenda of progressive science education, we need to be clear about the way student authority has to be combined with disciplinary accountability for learning science with understanding.

Everyday thinking is also not completely distinct from scientific thinking, and considering the aspects of continuity between them has done much to help our understanding of science learning. At the same time, getting a handle on the ways in which they are distinct can help us view some aspects of science that are both overlooked and potentially fundamental to learning.

It is true that everyday ideas are critiqued in light of experience, and often they are revised. But the difference between this and science is crucial. For example, if I attempt to leave my neighbor's porch with the idea that the sliding door is open, and then bang my head into the glass, which is clean to the point of invisibility, I revise my idea and open the door before exiting. This experience would implicitly critique not only my idea about the door being open but would also likely motivate me to pay closer attention to the frame of that door in the future, to discern clearly whether it is open or closed.

In contrast, scientific knowledge is explicit, public, and a product of a community. Therefore, it is fundamentally first a social and then an individual aspect of reasoning. This is the case not only for the level of facts, on which level we typically consider scientific knowledge, but also on the levels of methods and values. Scientists express assertions about facts, the meanings of which are defined by explicitly accompanying methods. Critiques in science are also first explicit. It is only when they become appropriated through participation in practice that critique becomes a feature of individual reasoning. Then, when preparing a claim for public display, we may implicitly revise it in our thought. As such, the critique in *form* becomes implicitly a part of thought, similar to the critique of the sliding door on my idea about it. But this critique, because of its genesis on the social plane, is in its basic *quality*, different from everyday critiques. That is, it is about the particular and nuanced way science forms explicit connections between ideas and nature.

The explicit nature of scientific ideas and critiques may on the surface seem trivial, but it is in a way the most fundamental aspect of science for learning. Although they sometimes are, everyday ideas need not necessarily be explicit. For scientific ideas, their explicitness is what sets them apart, because without explicit formulations of facts and methods, there would be no science.[5] If students are to develop a grasp of practice, coming to understand the centrality of making claims and methods explicit is the first step. Without this, there would be no rationale for justifying claims (let alone a notion of "claim" to justify) and subsequently no awareness of the need to pay attention to explicit connections to nature when gleaning their meaning. Without an awareness of the underlying rhetorical basis of science, there is no reason to consider scientific knowledge as anything but mere facts about nature, similar in kind to a door being open or closed that, although not directly accessible, are uncovered by some special reasoning of scientists.

A final note on how this framework can help us think about learning involves the issue of misconceptions. From a "knowledge in pieces" (diSessa, 1988) point of view, concepts can be considered stable coherences of knowledge pieces (diSessa & Sherin, 1998). Consider the errors students often make. The specialized concept of mass is often confused with the concept of weight. Students have difficulty distinguishing the concept of heat from temperature (Wiser, 1995). They have trouble understanding the concept of pressure, often confusing it with more colloquial meaning of the term (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Students often do not distinguish voltage from current (Geddis, 1993), and the list goes on. What have been documented in the literature as misconceptions may, in part, be artifacts of knowledge pieces cohering around aspects of everyday sociocultural context when it is appropriate for them to cohere around scientific context. If students lack the sociocultural awareness to notice scientific ideas as such, then misconceptions might be a particular sort of category error. Would the same misconceptions manifest themselves if students *know that*, unlike everyday ideas, the informational content of a scientific concept is located in how it is operationalized and fits within the broader explanatory scheme, and *know how* to look for and find this informational content?

The view put forward here, by emphasizing the distinctiveness of scientific knowledge, highlights sociocultural resources that might influence the coherence states of knowledge. When a scientific claim is encountered by someone who has a grasp of scientific practice, that person has the resources to identify the informational content of the idea and has a notion of what it means to evaluate it in a scientific, rather than an everyday sense. Then that person has a scientific reason to believe it or not. Brewer and Samarapungavan (1991) argued that children's theories have a structure different from that of scientific theories, and this structure stems from the social contexts to which they belong: specifically, that the institution of science is responsible for the distinctiveness of its knowledge. The argument here could be seen as a development of this basic idea, with the added articulation of individual reasoning patterns that are key to participation in scientific practice. Although some initial hypotheses have been worked out here regarding how the interplay of construction and critique might influence science learning, this remains a sizeable and important area inviting future research.

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[5] See Olson (1996) for a related argument about how logic and rationality rest historically upon the development of writing.

PEDAGOGICAL IMPLICATIONS

This argument suggests a particular way of considering the pedagogical parallel between creating new knowledge and learning old. The analysis helps us see that having students learn knowledge in the ways that scientists created that knowledge is simply not workable. There is no need (nor is it possible) for students to recapitulate the full-blown processes that gave rise to each scientific idea. This becomes clear when we realize the work involved in debating the minute details of explicit connections to nature's behavior. If students engaged in full-blown material and social aspects of practice in such debates, very few scientific ideas could be learned.

That is not to say students should not engage in the full-blown material and social aspects of scientific practice for *some* ideas. This seems desirable, in fact, if we view a grasp of practice as a fundamental learning goal and if engaging in practice thus defined supports learning it. As such, the analysis suggests an important distinction in learning goals: For a grasp of practice, students should engage in authentic generation of scientific knowledge. For learning content, students should be supported to identify the dimensions of its information in terms of coordinated facts, methods, and values.

Pedagogy for Supporting a Grasp of Practice

First, consider implications for pedagogy when students are engaged in generating new knowledge to learn a grasp of practice. Teaching through this version of inquiry does not mean a pedagogical "letting go," or a bestowal of unaccountable epistemic authority on students. The kind of pedagogy involved in helping students attain a grasp of practice is quite directive. It is directive, however, less in terms of how to construct a claim than how to critique it.

In most inquiry classrooms, support for construction is the primary focus. Often this support is built into a general structure for constructing knowledge that itself serves as a learning goal, be it manifested in a computer environment (Edelson & Reiser, 2006; Sandoval & Reiser, 2004) or general categories that comprise an argumentation scheme (e.g., Erduran et al., 2004). The idea is to get students to act in a particular way, to construct knowledge claims. When they do not, instruction is envisioned as direction for the constructive effort.

The analysis of scientific practice and reasoning above suggests that to attain a grasp of practice, students need to learn how to play *both* roles and play them as they interact to ground authority and accountability in science. In such a classroom, instructional pressure would not be directive on how to *construct* a scientific claim or argument in this vision, but primarily on how to *critique*. Student-to-student critiques, when done well, then should drive the construction of new knowledge claims and their explicit connections to nature. Support for students to critique each other is present in other pedagogical designs (e.g., Hatano & Inagaki, 1991; Herrenkohl & Guerra, 1998), but not with the coherent appeal to a grasp of practice put forward here. More importantly, the few instructional designs that include explicit instructional attention to critique are the exception.

Authority in this pedagogical scheme lies in the classroom community, but this does not imply that "anything goes" or that the teacher has no voice. The teacher supports formation and operation of a community that understands its responsibility to decide what counts as a new knowledge claim. Once formed, the teacher off-loads epistemic authority to this community. The teacher should avoid holding exclusive claim to epistemic authority. But by playing the role of critiquer in the community, the teacher can and should point out problems with knowledge claims, noting relevant errors in the chain of evidence through which an explicit connection to the behavior of nature is made. This way, the teacher has a voice, and a privileged one, but it is through the role of critiquer that the students themselves are expected to play and are learning to play. Thus, the teacher's critiques should function not only to identify errors, but also to model the kind of thing that students are expected to do with their peers' and with their own knowledge claims.

Moreover, although epistemic authority becomes an emergent outcome of a functioning classroom community, other forms of authority must remain with the teacher. For example, the teacher's logistical authority is essential for maintaining order and for shaping the necessary aspects of the activity: getting the students to work in groups, to give their intellectual energy to the issues at hand, to present their work to each other clearly, and to critique each other. Students will not do these kinds of things on their own without a teacher's exertion of logistical authority. But logistical authority is distinguished from epistemic authority, which is authority for deciding what counts as a new knowledge claim.

Pedagogy for Learning Content

Finally, consider implications for pedagogy when students are engaged in learning old knowledge. Students should be supported to understand ideas through their explicit connections to nature's behavior in data. Students need to be able to understand what data displays mean, and how to draw the connections that a scientist would between facts, methods, and values. Because students are not likely to know how to do this, they need to be taught.

One way to conceive of this is in terms of "problematizing" content advocated by Engle and Conant (2002) and others (e.g., Reiser, 2004). Ideas should not simply be brought into a classroom and explained, but should be problematized. That is, students should be asked to articulate interpretations of scientific ideas in light of data, entertain alternative possibilities, and try to achieve consensus. This idea of problematizing claims has also been developed in mathematics education and advocated as a way of organizing teaching of all academic disciplines (Hiebert et al., 1996). Problematizing ideas "opens up" a space within which alternative interpretations are likely to emerge. Pedagogy then can support resolution in ways that parallel their resolution in the discipline, which for science means in light of methods and values. Thus, a science-specific formulation of pedagogy that problematizes and resolves student interpretations of content could draw on the model for interpreting content put forward here. Knowing how to question content requires knowing the way content is questioned and held accountable in the discipline, which in science means a grasp of practice and the *knowing that* and *knowing how* involved.

Although a grasp of practice as a resource for learning scientific content provides us with a way of distinguishing different learning goals, these may not always be distinguished as clearly in actual teaching. Some activities should foreground grasp of practice as a learning goal, and some activities should foreground content understanding. Learning a grasp of practice and learning content are likely to unfold iteratively. That is, the learning of some content, particularly when the roles of constructor and critiquer are simulated accurately, is likely to support a grasp of practice, which in turn is likely to support learning of subsequent content. Over time, the process is likely to be similar to the development documented by several mathematics educators who have worked on the emergence of "sociomathematical norms" in student mathematical sense making (Yackel & Cobb, 1996). In mathematics, this has been documented as learning that unfolds in an iterative manner over months and years. It is likely to be the same in science.

CONCLUSION AND FUTURE RESEARCH

This vision of pedagogy for learning content in a disciplinary way has the potential to broaden our conception of what it means to understand scientifically. Much work has been dedicated to pedagogy for understanding, with substantial benefit for science teaching. Generally, however, research on teaching for understanding has focused on content primarily in terms of facts. For understanding facts, teaching for has appealed to analogies (e.g., Clement, 1993) and demonstrations (Minstrell & Stimpson, 1996). The focus has been on efforts to reorient students to a new way of interpreting phenomena through acquisition of causal mechanisms, concepts, and the like. This notion of understanding is important, but it is not enough. Precisely how important this additional notion of understanding is for learning, retention, and flexible use of knowledge is an open question inviting more research.

Subsequent research should also elaborate on the theoretical sketch of scientific practice, reasoning, and learning presented here. The sketch will further develop as it is filled out by empirical detail. Precisely how and under what conditions does a grasp of practice influence reasoning and learning of content? How does it support a clear understanding of how and why “cutting edge” science deserves more skepticism than “settled science?” How could it be taught to support appropriate reactions to scientific claims in the public sphere?

And as stated at the outset, this theoretical sketch invites alternatives. What are other ways that scientific practice, reasoning, and learning may be related? Recent advances in science studies and learning theories provide a rich set of resources for addressing this. Drawing coherent connections among these is necessary for developing curricular theory and is a timely opportunity that our community must meet.

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