EDUCATIONAL PSYCHOLOGIST, *39*(1), 57–68


# Epistemological Resources: Applying a New Epistemological Framework to Science Instruction

Loucas Louca
*Department of Curriculum and Instruction*
*University of Maryland, College Park*

Andrew Elby
*Department of Physics*
*University of Maryland, College Park*

David Hammer
*Department of Curriculum and Instruction and Department of Physics*
*University of Maryland, College Park*

Trisha Kagey
*Montgomery County Public Schools*



Most research on personal epistemologies has conceived them as made up of relatively large, coherent, and stable cognitive structures, either developmental stages or beliefs (perhaps organized into theories). Recent work has challenged these views, arguing that personal epistemologies are better understood as made up of finer grained cognitive resources whose activation depends sensitively on context. In this article, we compare these different frameworks, focusing on their instructional implications by using them to analyze a third-grade teacher's epistemologically motivated intervention and its effect on her students. We argue that the resources framework has more predictive and explanatory power than stage- and beliefs-based frameworks do.

As teachers and science education researchers, our interest in personal epistemologies stems largely from their effect on students' learning of science. Students holding more sophisticated epistemological views tend to approach learning more actively and tend to acquire a better conceptual understanding (Linn & Songer, 1993; Schommer, Crouse, & Rhodes, 1992; May & Etkina 2002; Hammer 1994). Classroom interventions aimed explicitly at addressing students' epistemologies can lead to improved learning (Carey & Smith, 1993; Linn & Hsi, 2000; Smith, Maclin, Houghton, & Hennessey, 2000).

Given the importance of epistemologies for learning, how can teachers foster epistemological sophistication most efficiently? The answer, we argue in this article, depends on the form of students' personal epistemologies and on teachers' perceptions of that form. By "form" we mean the grain size, stability, and context dependence of the relevant cognitive elements. Some researchers view epistemologies as developmental stages (King & Kitchener, 2004), others as collections of beliefs (Schommer-Aikins, 2004). We view epistemologies as constructed from finer grained cognitive elements, as described later in this article.

In this article, we apply these three theoretical frameworks—developmental, beliefs, and resources—to a third-grade science conversation motivated by the teacher's epistemological diagnosis of her students' difficulties. After comparing the frameworks, we evaluate which one has the most descriptive, predictive, and explanatory power with respect to the teacher's interventions and the students' reactions to them.

## THE FORM OF EPISTEMOLOGIES

Most research on epistemologies has assumed them to consist of developmental stages or beliefs. We review those

Requests for reprints should be sent to Loucas Louca, Department of Curriculum and Instruction, University of Maryland, 2226 Benjamin Bldg., College Park, MD 20742. E-mail: LL109@umail.umd.edu

frameworks and their instructional consequences. Then we outline our own framework.

### Epistemologies as Developmental Stages

In this view, epistemological development resembles cognitive development as conceptualized by Piaget and National Froebel Foundation (1967), or moral development as conceptualized by Kohlberg (1981). For instance, in the seven-stage scheme of King and Kitchener (1994), children initially view knowledge as comparatively certain and gained from authority or direct observation. From there they progress to relativist stages in which they view knowledge as constructed and different viewpoints as valid. Finally, some reach expert stages in which they see knowledge as constructed yet subject to scrutiny, judgment, and synthesis. This and similar developmental schemes (e.g., Belenky, Clinchy, Goldberger, & Tarule, 1986) build on Perry (1970). Invoking more recent developmental theorists such as Rest (1979) and Fischer (1980), King and Kitchener (2004) adopt a "complex stage theory" in which a typical subject's epistemology is like a wave spread over two stages.

Much of the pedagogically relevant research done in this framework focuses on developmental limitations. For instance, Kuhn (1989) studied children's ability to separate the effects of different variables while figuring out the behavior of virtual balls in a computer program. From children's difficulties with this and other tasks, Kuhn inferred developmental constraints on students' abilities to think abstractly about theory and evidence. Responding to Metz (1995), Kuhn (1997) spoke in terms of developmental guideposts rather than constraints. And King and Kitchener (2004), paraphrasing an aspect of Fischer and Pruyne (2002), note that a students' optimal level of performance, achievable with "contextual support and practice," can correspond to a different stage from their functional level of performance. Still, as Siegler (1996) argued regarding stage theories in general, these accounts leave much open with respect to mechanisms for variation and development. As such, they offer limited guidance for teachers.

### Epistemologies as Beliefs

Instead of treating a student's epistemology as a unified whole, many researchers tease apart different dimensions (Hofer & Pintrich, 1997), such as structure of knowledge, certainty of knowledge, and source of knowledge. Students' views along each dimension are assumed to consist of semi-independent beliefs. For instance, a student could hold sophisticated views about the structure of physics knowledge, seeing it as a hierarchy of concepts rather than as a bunch of equations, while also holding naïve beliefs about the certainty of that knowledge, viewing new theories as fixed and absolute.

Some researchers view epistemological beliefs as comparatively global (Schommer, 1990), while others have investigated how epistemological beliefs vary by discipline, for example, in chemistry versus psychology (Hofer, 2002a). What they all agree upon, however, is that epistemologies consist largely of comparatively stable, robust cognitive structures corresponding to articulate, declarative knowledge. These *beliefs* are taken to be the units—the cognitive "atoms"—of epistemologies.

Methodologically, it follows that researchers can probe a student's epistemology by clinical interviews and also, in less depth but more breadth, by surveys such as Schommer's (1990). Just as you can probe a child's ice cream preferences by simply *asking* the child about favorite flavors rather than by actually observing the child's behavior in an ice cream parlor, you can probe a student's epistemological beliefs simply by asking.

With beliefs as the cognitive units, fostering students' epistemological development is largely a matter of changing their beliefs. On this view, as Hofer (2001) noted, the first step is to destabilize naïve beliefs, analogous to eliciting and confronting misconceptions in science as a first step toward conceptual change (Posner, Strike, Hewson, & Gertzog, 1982).



### Epistemologies as Built From Fine Grained Cognitive Resources

We have begun to sketch an alternative view of naïve epistemologies as made up of *resources*, units of cognitive structure at a finer grain size than stages, beliefs, or theories (Hammer & Elby, 2002), analogous to diSessa's (1993) phenomenological primitives ("p-prims") in intuitive physics. Rather than attribute to children any general epistemological beliefs or theories, we understand them to have a range of cognitive resources for understanding knowledge.

Consider a 6-year-old child's views about the source of knowledge. When asked how she knows what's for dinner, the child says, "Because Daddy told me!" This answer reflects an understanding of knowledge as something that can be transmitted from one person to another. However, asked how she knows her mommy brought her a present, the same child says, "I figured it out, 'cause it's my birthday and I saw you hide something under your coat!" This answer reflects a rudimentary awareness of knowledge as something constructed out of other knowledge.

That is, the child has resources for viewing knowledge as transmitted *and* for viewing it as constructed. We call these resources *knowledge as transmitted stuff* and *knowledge as fabricated stuff.* Our framework posits these and other resources regarding the source of knowledge, as well as resources for understanding forms of knowledge (e.g., *stories, rules, facts*), stances (*acceptance, puzzlement, doubt*), and so on. Different contexts[1]—knowing what's for dinner and inferring the presence of a present—activate different resources. Neither one of those resources corresponds to the child's "real" epistemological belief about the source of knowledge.

Why not just say the 6-year-old birthday girl actually *has* (at least) two different beliefs about the source of knowledge, beliefs that don't conflict because they apply in different contexts? We think "belief" connotes a degree of stability and articulateness not properly attributed to the child's views about knowledge—at least, not until her epistemological resources reach a certain degree of organization, robustness, and conscious reflection. In other words, the difference between naïve and expert epistemologies lies not just in the content (views), but also in the form of the relevant cognitive elements.

For instance, an educational psychologist interested in science education undoubtedly possesses full-fledged, conscious beliefs, or even a theory, about the constructive nature of science knowledge, beliefs that do not vary loosely by context. The resources framework views those beliefs as a compiled, rich network of finer grained cognitive resources, including *knowledge as fabricated stuff* and others concerning the complex nature of scientific knowledge. By contrast, the birthday girl's "views" about the constructive nature of knowledge are tacit (usually beneath consciousness), less articulate, and more sensitive to changes in context about which the child is not consciously aware. The evidence discussed below suggests that the epistemologies of older children and adults display similar tacitness and context sensitivity, to a lesser extent. In summary, our framework attributes epistemological beliefs to experts and to some thoughtful novices, but views those beliefs as constructed from finer grained resources that novices also possess. The child's "constructivist" views are less rich than the educational psychologist's because the child, while having *knowledge as fabricated stuff,* lacks a more developed network of compiled resources.

This distinction between resources and beliefs has methodological implications. We are hesitant to infer a belief from statements within a single context. Only after checking for consistency, stability, and articulateness across multiple contexts do we infer a belief rather than the context-dependent activation of resources. Thus, we question inferences about students' epistemologies based solely on surveys or clinical interviews.

This framework, and the term "resources," has its origins in Minsky's (1986) computational model of mind as a "society" of "agents," at varying levels of structure. In fact, developmental psychology has moved in similar directions (Feldman, 1994; Karmiloff-Smith, 1992; Siegler, 1996). For instance, Siegler (1996) argued that instead of having a single theory- or belief-like way of understanding various phenomena, children have multiple ways of interpreting the world. Different contexts trigger different resources. Reviewing his own and others' research that challenge stage-based accounts of development, Siegler cited evidence of early competence and context-sensitive variability—the "ubiquity of multiplicity":

> The data … argue for a move away from universalist and comparative approaches and toward approaches that recognize as a central phenomenon the pervasive variability in children's thinking. This variability seems to be present in every area of higher level cognition, just as at all lower levels. (p. 81)

Siegler (1996) bemoaned the lack of mechanism in developmental accounts—how does change come about? He attributed the problem to oversimplified characterizations of reasoning abilities, arguing that "our difficulty in understanding change seems in large part attributable to our failing to acknowledge the omnipresence of variability and choice in children's thinking" (p. 16). For example, Crowley and Siegler (1999) modeled children's reasoning in terms of tacit "choices" from a range of possible strategies. Our approach is similar: We are working to model personal epistemologies as context-dependent activations ("choices") of resources.

We can clarify the resources framework by applying it to a result in the teacher epistemology literature. A teacher's *professed epistemology*, the stated views about knowledge and learning, can differ substantially from that person's *enacted epistemology*, the views about knowledge and learning an observer would infer from classroom behavior (Hofer, 2002b; Tobin & McRobbie, 1997). For us this is a matter of different resources getting activated in the two contexts, the hubbub of the classroom versus the reflective calm of a clinical interview. Neither the professed nor enacted epistemology is the teacher's "true" epistemology. The same mechanism accounts for observed variations (Bell & Linn, 2002; Leach, Millar, Ryder, & Sere, 2000; Roth & Roychoudhury, 1994; diSessa, Elby, & Hammer, 2002) between students' professed and enacted epistemologies, as well as within students' (or teachers') enacted or professed epistemologies.

Perhaps the starkest difference between the resources framework and its predecessors emerges in discussions of instructional implications. Instead of trying to confront and replace students' beliefs or trying to provide the extensive contextual support and practice needed to help students reach the top of their developmental range, a teacher could think instead of helping students "find" and apply productive resources they use in other contexts but fail to activate in science class (Hammer & Elby, 2003).

[1]In this paper, we rely on a colloquial, nontechnical sense of the word *context*. A change in context can be disciplinary (e.g., chemistry vs. psychology), social (a formal debate vs. a playful argument), emotional (a high-stakes test vs. an ungraded diagnostic test), topic-related (a discussion of the causes of racial inequality vs. a discussion of the causes of high health-care costs), and so on.

## COMPARING THE DIFFERENT FRAMEWORKS

Each of these frameworks is motivated and supported by a body of evidence. Here, we consider how a resources framework might account for the evidence supporting the developmental or beliefs frameworks. Similarly, we explore how those previous frameworks can explain the evidence cited earlier in support of the resources perspective.

### Developmental Stages Versus Resources

*Can the resources framework account for evidence supporting the developmental perspective?* We focus on what we take to be the most well developed of these schemes. King and Kitchener's (1994) Reflective Judgment Interviews asked participants about controversial, unsettled topics such as the trustworthiness of the news media, focusing on how the participants said they form and evaluate knowledge claims. Participants' responses were assigned to one of seven developmental stages. Overall, a student was usually assigned to a dominant and an adjacent subdominant stage. King and Kitchener found that these stage assignments predicted what reflective reasoning style participants would employ when grappling with other controversial issues.

In our view, this evidence suggests that reflective discussion around any one of a set of unsettled, controversial topics comprises a context for many individuals that reliably activates certain sets of epistemological resources. That is, they experience these as a particular kind of conversation, and part of that perception entails activation of a set of resources. E. F. Redish (personal communication, June 21, 2003) suggested this perception comprises a "framing" as discussed in linguistics research (Tannen, 1993). The evidence does not address whether individuals' assessed stages predict their epistemology when, for example, they discuss more "settled" topics, or when they are learning science in a classroom. These alternate contexts may trigger other epistemological resources, just as "How do you know what's for dinner?" triggers different resources than does "How do you know Mommy brought you a present?"

Further evidence supporting the developmental perspective is that, in general, older and/or more educated people tend to show more sophisticated epistemologies, and individual students generally progress through the stages in order (King & Kitchener, 2004). From a resources point of view, much as in Siegler's (1996) perspective, at very early ages the fundamental resources are forming; a 2-year old child would not be able to answer "How do you know____?" Later, as people gain experience with knowledge and learning, their epistemological resources should become more richly interconnected, compiled, and articulate. Furthermore, the contextual cueing strengths evolve, so that some epistemological resources become activated more strongly and more often, and in association with other resources. This mechanism allows for the appearance of age- and education-dependent epistemological patterns. The resources view, however, predicts that any individual would display a wide range of epistemologies and that many developmental limitations may be less limiting than they appear. So, like Siegler, we adopt a developmental but non-stage-based view of how epistemologies change over time.

*Can the developmental framework account for the evidence supporting the resources perspective?* The resources framework is designed to account for evidence of variability within a given subject's epistemology:

1. In the birthday girl's ability to understand knowledge in different ways when asked different questions.
2. In differences between professed and enacted epistemology, for both teachers and students (Hofer, 2002b; Tobin & McRobbie, 1997).
3. Across contexts *within* a given discipline (Bell & Linn, 2002; Leach et al., 2000; Roth & Roychoudhury, 1994; diSessa et al., 2002).

To account for such variation, a stage theorist might invoke a version of decalage (Piaget & National Froebel Foundation, 1967; Flavell, 1963), the notion that a student performs at different levels on formally similar tasks. In particular, Fischer's skill theory (Fischer, 1980; Fischer & Pruyne, 2002), characterizes a subject by a multistage developmental range that extends from the *functional level* (displayed in everyday situations) to the *optimal level*, a developmental upper limit the student exhibits with the right kinds of contextualized support. As King and Kitchener (2004) note, "contextual support" can include giving students an advanced example of the desired skill, a chance to ask questions about that example, opportunities to practice the skill in multiple contexts, and so on.

For two reasons, we do not think that a stage-based account of epistemology—even one informed by Fischer—can adequately explain the three kinds of variables listed earlier. First, much of the aforementioned within-subject variability spans the entire developmental spectrum and occurs even when the context varies minimally. For instance, Leach et al. (2000) asked high school and university science majors two rounds of questions about the construction of scientific knowledge. One round consisted of Likert-type scale items based on decontextualized dichotomies such as "It is *not always* possible to tell which is the most powerful of two competing theories, no matter how many data are available" versus "It is *always* possible to tell … ." The second round of questions was deeply contextualized within a story: Superconductivity researchers at a conference argue about how to interpret a given data set. The authors carefully evaluated the validity of their items. Yet, even within each round of questions, most students' answers ranged from absolutist (the data unproblematically lead to a given conclusion) to reflective (interpretation involves a complex interplay of theory and evidence), covering almost the entire developmental spectrum of King and Kitchener's scheme. The variation within a given round of questions cannot be explained in terms of contextual support and practice.

Our second reason for denying that stage-based developmental schemes can adequately explain within-subject variability builds on Siegler's (1996) complaint that stage-based accounts of such variation fail to identify a mechanism for its occurrence. Formulating such a mechanism involves opening up the "black box" of a developmental stage and exploring the finer grained cognitive elements within. The resources perspective provides a framework for describing and analyzing those finer grained elements.

## Beliefs Versus Resources

*Can the resources framework account for evidence supporting the beliefs perspective?* This evidence includes the existence of belief-like epistemological dimensions inferred from detailed interview data (Hammer, 1994) and from statistical factor analysis of survey data (Schommer 1990). Other evidence establishes which of these beliefs correlate with students' learning in different disciplines (Schommer et al., 1992; Schommer 1993).

In our view, these important studies do not favor the beliefs framework over the resources framework; both frameworks account for the results equally well. For instance, Schommer et al. (1992) found that students' professed epistemologies concerning the structure of knowledge (simple vs. complex), but not their professed epistemologies about the certainty of knowledge or the quickness of learning, correlated with their comprehension of a mathematics textbook passage. The effect remained even when confounding factors, such as prior mathematics instruction, were controlled for. A beliefs advocate assumes that the professed epistemology elicited by the Schommer et al. survey reflects *beliefs* that the student brings to bear when tackling the mathematics passage. A resources advocate, by contrast, expects differences between professed and enacted epistemologies. That expectation does not rule out correlations; in fact, the weak correlation that Schommer et al. found between professed epistemologies about the simplicity of knowledge and professed study strategies ($r$ = 0.19) suggests some correspondence but hardly a general coherence. A strong correlation, by contrast, would count as evidence that students' views about the structure of knowledge are full-fledged beliefs that drive behavior.

A greater challenge to resources advocates lies in claims that students' interview data fall into neat belief-like categories, or that survey data produce cleanly separated factors. We have two responses. First, as Hofer and Pintrich (1997) and others have noted, when factor analysis is performed on individual items rather than on clusters, the resulting factors are less stable and involve less dramatic correlations between the items within the factors.

Second, even when a student displays consistent "beliefs" in one context, such as a particular survey or interview format, we cannot infer that the student would display the same views in another context. For instance, while interviewing physics students taking a particular class, Hammer (1994) stayed close to the course in terms of the questions ("How is the course going?") and the think-aloud tasks (involving homework problems and textbook passages). He found strong patterns in students' epistemologies, which he characterized as "beliefs" in that context. However, he noted that different contexts —ones further removed from the course—might elicit different views. And indeed, diSessa et al. (2002) found that Hammer's (1994) framework could not capture the epistemology of a student engaged in clinical interviews centered around qualitative understanding of physics concepts—a very different context, unfortunately, from her introductory physics course. Other research also supports this nonbelief-like context sensitivity in students' epistemologies, even within a discipline (Bell & Linn, 2002; Leach et al., 2000; Lising & Elby, 2003; Roth & Roychoudhury, 1994). In summary, the resources framework can account for the sorts of consistency evident within most research on epistemologies by emphasizing that those question-to-question correlations are hardly perfect and arise within a single context.



*Can the beliefs framework account for evidence supporting the resources perspective?* Here, we refer to results 1 through 3 from the earlier discussion about whether the developmental framework could account for evidence supporting the resources perspective. For the first of the three results, a beliefs advocate could claim that the birthday girl doesn't *have* a "constructivist" belief, begging the question of what she *does* have that enables her to think of knowledge as something she can figure out, in certain contexts.

For the second result, in cases where enacted and professed epistemologies disagree, a beliefs advocate could claim that epistemologies are by definition declarative and articulate, in which case the professed epistemology is the subject's actual epistemology. Indeed, in some cases it is clear that "habits" overwhelm articulate beliefs. We expect, however, that if teachers hold stable, articulate epistemological beliefs, then with deliberate reflection they would readily become aware of inconsistency between those beliefs and their classroom behaviors. In fact, teachers are generally not aware of these inconsistencies (Tobin & McRobbie, 1997). In any case, this nonepistemological explanation could not account for the third result, the evidence of within-subject variability within a given context (professed or enacted).

Finally, for results 1 through 3, the beliefs advocate might say that *beliefs* can vary, not only between disciplines but also between different contexts within a given discipline. This line of reasoning is consistent with the resources framework, and we need to emphasize its implications: If a student can have three or four contradictory context-dependent beliefs about the structure of physics knowledge, for example, then a "belief" we attribute in one context would not necessarily apply in another. Nor would we expect students in a given context to be articulately aware of their beliefs that apply in other contexts. In effect, this response is to adopt a resources framework, except for the terminology.

## CHILDREN'S EPISTEMOLOGIES IN A DISCUSSION ABOUT AUTUMN LEAVES

We now turn to our case study of a third-grade lesson taught by the fourth author, a public-school teacher in Montgomery County, Maryland.[2] Our interest stems from the teacher's interpretation of an epistemological (as opposed to conceptual) difficulty and her subsequent interventions.

### Background Information for the Case Study

First, we briefly review the topic of the lesson, the relevant research on student thinking, the epistemological issue involved, and our approach to analyzing students' epistemologies.

#### *"Why Do Leaves Change Color?"*

This is a familiar lesson theme from elementary science curricula. Our concern here is with the epistemology embedded in understanding what the question is asking.

A scientist might interpret it in terms of what happens in the leaf. If exploring the question for the first time, a scientist might consider, for example, whether colored liquid comes into the leaves from the tree. A scientist could also interpret the question as asking about evolution: What was the selective advantage that favored trees with this property? Both interpretations involve mechanism: The former concerns the proximal mechanism for how the change occurs in a leaf; the latter concerns the evolutionary mechanism for how trees acquired this property.

By contrast, science education research shows that children often respond to such questions in nonmechanistic ways, often reflecting teleological ("purpose"-based) and anthropomorphic reasoning (Tamir & Zohar, 1991).

Most work on this topic (Zohar & Ginossar, 1998) frames the issue in terms of conceptual frameworks. Southerland, Abrams, Cummins, and Anzelmo (2001) recently applied diSessa's (1993) framework to posit a context-sensitive account of a primitive sense of mechanism in biology, of "need causing change." In this paper, we support the notion that children's teleological (and other) reasoning about leaves is sensitive to context. But rather than interpret children's reasoning in this respect as reflecting a primitive sense of mechanism, we interpret it in terms of epistemological resources.

#### *The Relevant Epistemological Issue*

Following Hofer and Pintrich (1997), we define "epistemology" as a person's views about the nature of knowledge and knowing. A student's views about the structure of knowledge, although usually coded as *simple* or *complex*, may also include finer grained views about what forms (kinds) of knowledge there are and how they relate. For instance, does the student view a fact as a different kind of knowledge from a theory or a rule? When presented with an example of knowledge and asked "What kind of knowledge is this?" what other answers might the student give?

A resources advocate assumes that people have resources for understanding a variety of forms of knowledge, such as stories, rules, games, facts, and so on. Another division between different kinds of knowledge is *teleological* versus *mechanistic*: Is scientific knowledge teleological, explaining events in terms of "purpose," or is it causal, explaining events in terms of mechanisms?

A critic could deny that this distinction is epistemological, on the grounds that "teleological" and "mechanistic" are different kinds of explanations, not different kinds of knowledge. However, a student who thinks scientific knowledge can include explanations in terms of purpose has different views about the nature of scientific knowledge than does a student who thinks scientific explanations must be causal. So, even if the distinction between teleological and mechanistic isn't in itself epistemological, a person's judgments about which kinds of explanations can "count" as scientific knowledge is epistemological. More generally, the debate over which kinds of explanations can "count" as knowledge in which contexts is an epistemological issue.

A beliefs advocate such as Schommer can probably accept this distinction as epistemological on the grounds that someone who differentiates teleological from mechanistic knowledge views knowledge as more complex—specifically, as having more internal structure—than does someone who fails to make that distinction. A developmental psychologist can trace this distinction to Piaget and National Froebel Foundation's (1967) genetic epistemology: Children progress from stages in which they explain phenomena teleologically to stages in which mechanistic explanations predominate.

According to our framework, adults have epistemological resources for distinguishing mechanistic from teleological knowledge and for navigating between them. To demonstrate this point, we consider a hypothetical "vacuum guy" showing his new high-tech vacuum cleaner to his roommate:

Vacuum guy: … And the brush roller switches on automatically when the vacuum goes onto car-

[2]We analyzed this conversation as part of a larger project, *Case Studies of K–8 Student Inquiry in Physical Science*, to develop a collection of case studies as materials for teachers' professional development.

pet, without you having to push a button or anything.

Roommate: Why does the brush turn on over carpet?

Vacuum guy: To stir up dust that's ground in.

Roommate: No, I know, but why, how does it turn on?

Vacuum guy: Oh. The salesman said something about a laser beam reflecting less brightly off carpet, and a sensor … .

Vacuum guy initially assumed his roommate wanted a teleological explanation of the roller brush's purpose. But the roommate's "No … why, *how*" signaled a desire for a mechanistic explanation of how the brush turns on. Vacuum guy was able to read these cues and switch the substance of his explanation. This indicates that his epistemological resources—his knowledge about different kinds of knowledge and the distinctions between them—played a role. If vacuum guy possessed no epistemological resources for understanding knowledge as mechanistic, he simply would not have understood why his roommate was dissatisfied with his first answer and what his roommate was actually asking.

### Inferring Students' Epistemologies From Classroom Behavior

In this article, we explore students' enacted epistemologies by observing how they treat knowledge in the process of forming "scientific" explanations. We acknowledge the dangers of this approach. For instance, we do not think behavior consistent with a given view of knowledge automatically indicates the activation of the corresponding epistemological resources. So, we distinguish between the (meta)cognitive resources for treating knowledge in various ways, and the epistemological resources for what Kitchener (1983) called "epistemic cognition," cognition about knowledge and knowing. We can infer epistemology from behavior when evidence suggests the involvement of knowledge about knowledge.

Vacuum guy illustrates such an inference. It's unlikely he just "fell" out of a teleological treatment of knowledge and into a mechanistic one. Rather, he switched because of his (revised) knowledge about the kind of knowledge his roommate was seeking. The involvement of vacuum guy's knowledge about knowledge implicates the activation of epistemological resources.

Why not just *ask* students questions that probe their views of scientific knowledge as teleological versus mechanistic? Because their professed and enacted epistemologies sometimes align poorly, and we are interested in the effect of epistemology on students' learning. The enacted epistemology displayed *during* the learning process is most likely to contribute to these effects (Hogan, 1999).

## Applying the Frameworks to Classroom Data

Now we present the classroom data, broken into segments. After each segment, we discuss what the three frameworks say about the teacher's and students' behavior and about what might happen next.

### Segment 1: The Teacher's Diagnosis and Initial Intervention

In her previous experiences teaching about leaf color changes, "Miss Kagey" (as students call her) noticed a tendency toward general, descriptive explanations ("They get really old and they're dying") and explanations in terms of purpose ("In the winter I don't think the tree needs the leaves"). She wanted students to reason more mechanistically on the specific question of leaf color, not so much to help them understand why leaves change color, but to guide them toward mechanistic scientific reasoning in general. To tease apart teleological from mechanistic reasoning, Miss Kagey asked the question in two ways. She expected the first, "Why do leaves change color?" to elicit the usual kinds of nonmechanistic responses. The second question was, "What is happening inside the leaf in order for the leaf to change color?"

She started by giving students several minutes to write their responses. The first question drew the kinds of answers she expected. Some students answered in very general terms, whereas others answered in anthropomorphic or teleological terms, that "leaves change color because that is their way of getting ready for winter" (Beatrice), or "because that means they're dying" (Bharat).[3] Only a couple of students responded with ideas that expressed or hinted at specific mechanism.



Next, the teacher began a full-class discussion focusing on the first question. Her strategy was eventually to contrast the kinds of answers the students' gave to that question with the more mechanistic ones she hoped the second question would elicit. She began with an analogy:

2. Teacher:[4] Ok, I asked you two questions and I want to go through the two questions and how they're different, and then we'll start talking about one of the questions. The first question is "Why do the leaves change color?" […] And the second question was "What's going on—what's going on inside of the leaf that makes it change color?"—something like that. And Bharat asked me "How is that different?" And the way I explained it to him is [by asking] "Why are you hungry?" And you say, "I'm hungry because I haven't eaten since eight o'clock in the morning or six o'clock in the morning." And the second question says "How—what is going on inside of your body that's making you hungry?" You can say, "The food already went into my stomach, my stomach already digested it, and now my stomach is empty and that's why I'm hungry." So, you are talking about what's going on. "What things are going on inside of the leaf—what things are going on inside of your body to make you hungry?"

[3]We have Internal Review Board permission to use students' first names.

[4]Number before quotation refers to the line number from the full transcript of the conversation.

In the ensuing discussion, some students hinted at physical mechanism ("They fall off by the wind and stuff"), but almost all of them also referred to purpose or other nonmechanistic reasons.

Miss Kagey then turned the class's attention to the second question, again amplifying how it differs from the first:

38. Teacher: Let's move onto the second question. The question was … "What is going on *inside of*[5] the leaf that is making the leaf change color?" This is a "how" question. What's going on inside of it? This is another difficult one.

*Discussion.* We now discuss how the three frameworks describe the teacher's strategy of splitting the leaf question into two parts and amplifying that split with the stomach analogy.

A stage theorist could interpret the teacher's technique as an attempt to supply the "contextual support" needed to bring students from the functional level to a higher level within their epistemological developmental ranges. Miss Kagey assumed that the usual question, "Why do leaves change color?" elicits functional-level epistemologies, whereas "What's going on inside the leaves?" and the stomach example can elicit higher level epistemologies.

Alternatively, a stage theorist might say Miss Kagey's intervention is nonepistemological, an attempt to knock students into mechanistic reasoning without accessing their knowledge about knowledge. In this case, the developmental framework for describing epistemology has little to say about Miss Kagey's approach.

The beliefs framework also has little to say. Surely, rewording the question doesn't change students' beliefs about the teleological versus mechanistic nature of scientific explanations. So, a beliefs advocate, like some stage theorists, might claim that Miss Kagey's intervention isn't really epistemological in nature.

Because the resources framework predicts fine-grained context dependence in the activation of students' epistemological resources, it has more to say about Miss Kagey's strategy. She assumed that students have epistemological resources for viewing knowledge as mechanistic but tend to activate those resources fleetingly (if at all) during standard discussions of why leaves change colors. She tried to tap into those resources. According to Miss Kagey's account written at the time, she was trying to help students understand that "how" questions in biology require a different kind of answer drawing on a different kind of knowledge.[6]

We are not claiming that Miss Kagey was thinking formally in terms of epistemological resources. In fact, she was unaware of the epistemology research literature. Our claim is that the resources framework provides a language for describing Miss Kagey's diagnosis of her students' difficulties and her intervention. She wasn't trying to change students' beliefs about knowledge or to provide the extensive contextual support and practice that is often needed to help students reach their optimal stage. Nor was she attempting to sidestep students' views of knowledge by knocking them into a particular kind of thinking. Instead, she was trying to tap into students' epistemological resources for understanding the nature of causal, mechanistic knowledge forms and how they differ from teleological and general-description knowledge. So, compared to its predecessors, the resources perspective provides a better framework for describing and analyzing Miss Kagey's diagnosis of her students' difficulties and her intervention.

Did the intervention work? We invite the reader to make a prediction before reading the next data segment.

### Segment 2: Discussion of the "How" Question

For most students, Miss Kagey's initial intervention didn't work. Their spoken answers to the "how" question, like their original written responses, fail to display a stable commitment to mechanism, despite the teacher's repeated prompts:

43. Morgan: I think, … when it changes colors it sorta means like, I think it just sorta means like growing up … And, like, in Fall it like, it might be like the leaf's birthday. And, it's telling that it will have to fall off soon. …

44. Teacher: How is it happening? How is it happening?

45. Morgan: It's happening because, I think because of the weather, and because of the sun and water and because … For some reason I think of the seasons. I don't know why, but …

46. Teacher: That's a "why" question. What's going on inside the leave? Pass to someone if you're not prepared to answer. What's going on inside of the leaf that is making it change color? What's going on *inside of* the leaf that's making it change color? …

47. Camille: I think that it's … it's, um … it's getting food from the trees, so it, so it's like … I agree with Morgan because it's kinda like a life cycle of a caterpillar having … only changing colors.

48. Megan: Um … I think what's going inside a leaf, it's like if you like leave an apple out for a long while and it starts to change its color, I think that's how, um, it works with the same way as food, how it rottens …

*Discussion.* The students' responses hint at mechanism but don't show a commitment to it. Their difficulties may stem from a mixture of missing conceptual knowledge—they just don't know much about leaves—and missing or inactive epistemological knowledge about the mechanistic nature of scientific explanations.

What should the teacher do next? What guidance do the three frameworks provide? At this point, given students' persistent troubles despite repeated prompts, a stage theorist



[5]Italics reflect emphasis in voice.

[6]Ms. Kagey recorded her intentions and observations at the time and later turned them into a written and video "case study" of student reasoning.

might advise Miss Kagey either to give up on the grounds that she's running into developmental limitations, or to plan a sequence of activities designed to provide extensive contextual support to help students reach a higher stage within their developmental ranges. These activities could include more examples of the teleological/mechanistic distinction, opportunities to ask questions about those examples, and practice applying the distinction in some "easier" contexts.

A beliefs advocate might remain agnostic or might advise Miss Kagey to engage students in a direct discussion about their epistemological beliefs in order to diagnose her students' level of epistemological sophistication and to see what changes in beliefs might be needed.

A resources advocate, by contrast, would advise Miss Kagey to keep trying to tap into students' epistemological resources for understanding mechanistic knowledge. We expect third graders have such resources and apply them in more familiar, everyday contexts. For instance, consider a hypothetical third-grade soccer player. Her team just lost after a defender suddenly fell down, allowing the opponents to score. Her mom asks, "Did she fall because she's clumsy?" We can easily imagine the soccer player responding, "No, there must be some reason, like maybe there was a hole, or her shoe was loose … " Although the soccer player doesn't know the correct mechanistic explanation, she knows to look for one. This indicates an understanding—perhaps fleeting and context-sensitive—of mechanistic knowledge forms.

The soccer example is a plausibility argument that third graders have resources for understanding mechanistic knowledge forms, and it illustrates how we might search for those resources in students' everyday reasoning. It also suggests a strategy for activating those resources in science class: Temporarily bring the discussion to more familiar ground where mechanistic resources are more likely to turn on. That's exactly what Miss Kagey decided to do.

### *Segment 3: Miss Kagey's New Intervention*

The teacher tried a new analogy to illustrate the difference between (teleological) "why" and (mechanistic) "how."

52. Teacher: Think about it this way. Say I'm making cookies for my birthday because my birthday is coming up, right Kristina? And so I was making cookies for my birthday and the question was "Why am I making cookies?" What's the answer? Because it's my birthday. How am I going to make these cookies? Well, I'm going to put together a bunch of ingredients, put them inside of a bowl, mix it all up, put it into the oven, take it out of the oven, lay it out to cool off. They are two different questions. We talked about the "why" question. People said it gets cold, it's getting old, it's drying up, the wind is happening. Now I'm asking you the "how" question. How are the leaves changing color? *How* are the leaves changing colors? What process is it going through? What steps are happening inside of the leaf?

*Discussion.* As just discussed, this intervention is best predicted and described by the resources framework. Using a familiar scenario in which students readily distinguish purpose from mechanism, the teacher tried to turn on students' epistemological resources for understanding the difference between teleological and mechanistic knowledge forms.

Did the cookie intervention work? A stage theorist probably remains skeptical that the teacher has provided enough contextual support to help students reach the upper ends of their developmental ranges; if the stomach analogy didn't work for almost all the students, why would this one additional analogy make a big difference for many students? Although Miss Kagey provided specific examples of the epistemological "skill" she wants students to exhibit, she gave them minimal opportunity to ask questions about those examples and no opportunity to practice those skills in a different context. A stage-based developmental framework allows for the possibility that she has provided sufficient contextual support. But the framework provides no mechanism by which this might occur, and hence, no analytical toolbox for predicting what constitutes *enough* contextual support.

A beliefs advocate could frame the teacher's cookie intervention as helping students "remember" their more sophisticated epistemological beliefs about the mechanistic nature of knowledge, in which case students' subsequent explanations could become more sophisticated. But this line of reasoning, relying on the coexistence of teleological and mechanistic epistemological beliefs that are remembered or forgotten depending on context, fits more naturally into a resources framework. Alternatively, a beliefs advocate might classify the cookie intervention as nonepistemological, in which case the framework has little to say about its likelihood of success. A stage theorist might agree.

The resources framework, although not fleshed out enough to make a firm prediction, would give reason to suppose the cookie example could trigger students' "mechanistic" resources, enabling more commitment to mechanistic explanations—even though students haven't practiced the corresponding "skill" in another context.

### *Segment 4: The Post-Cookie Discussion*

After the cookie analogy, there was a brief pause, with a few students starting to speak but stopping. Then John took the floor.

57. John: I think it, like us, I think it has special cells in it that change color … [teacher requests clarification] … I don't think there's like a special type of warmth … I think there are basically cells in every type of living thing.

62. Christian: I think … when it's like gets really cold, like the veins, like, make it change all kinds of colors.

63. Teacher: This side of the room is full with ideas.

64. Beatrice: I think, um, the trees' color, because of the sun and the veins, the sun makes the veins turn, um, like yel-

low or red or any color. And then, it changes color because the sun, it's really hot, and then it's like …

At this point, Justin offered a nonmechanistic explanation, but then the mechanistic conversation continued:

68. Sam: What I think is going on inside the leaf is the stem is damming off, so that no more oozing it out of the leave, and no more blood can get into the leaf from the tree. And, all the pigment inside the leaf is getting all stuck in there … [7]

With dismissal time approaching, Miss Kagey asked students to write their new "best" answers to the leaf questions. Most students, even ones who didn't participate in the class discussion, wrote more mechanistic explanations than they had originally.

### *Overall Discussion of This Classroom Episode*

Given the failure of Miss Kagey's earlier interventions, the success of the cookie intervention is hard to explain within the developmental or beliefs framework. As noted above, a stage theorist could claim that the cookie example, perhaps combined with Miss Kagey's earlier interventions, provided enough contextual support to help students reach a higher stage within their developmental ranges. But this story has two problems. First, in a Piagetian framework (1967), the stages corresponding to teleological versus mechanistic explanations are widely separated. Presumably, the corresponding epistemological developmental stages are separated as well. In such cases, Fischer (1980) suggested, students generally need substantial contextual support and practice to "climb" up their developmental range, more than Miss Kagey provided. Second, the stage-based developmental perspective provides no toolbox for formulating a *mechanism* to explain why the cookie analogy, but not the stomach analogy alone, could knock students to a higher level of performance. For this reason, the developmental perspective is not the best framework in which to analyze the success and failure of Miss Kagey's various interventions.

As discussed earlier, a beliefs advocate has to claim either that Miss Kagey's intervention was nonepistemological, or that the cookie intervention helped students "remember" their nascent beliefs about scientific explanations. However, research carried out within the beliefs perspective suggests that children's epistemological beliefs are generally naïve (Schommer, 1990; Linn & Songer, 1993; Tsai, 1999). Triangulated with research on children's lack of skills needed to engage in deep scientific inquiry (Kuhn, 1989), this epistemological research makes it hard to maintain that elementary school children have quite sophisticated—but generally "forgotten"—beliefs about the mechanistic nature of scientific knowledge. Furthermore, although some beliefs advocates take beliefs to vary by discipline, none of them (to our knowledge) expect beliefs to vary in response to fine-grained contextual distinctions such as a stomach analogy versus a cookie analogy. More likely, a beliefs advocate would claim that the cookie intervention isn't epistemological, precluding an epistemology-based explanation of why it worked. A stage theorist could take the same tack.

The resources perspective, by contrast, provides a framework for exploring the context-sensitive ways in which students treat and view knowledge. The cookie intervention worked not because it changed or "recovered" students' epistemological beliefs, but rather because it brought students into a familiar situation in which they readily distinguish teleological from mechanistic knowledge forms. This allowed students to activate their epistemological resources for understanding the difference. Unlike its predecessors, the resources perspective invites research into the details of these context sensitivities, details involving cognitive elements that are finer grained than beliefs or stages. And those details are exactly what teachers like Miss Kagey work with every day.



## Is Our Account "Epistemological?"

Earlier, we promised not to infer a student's epistemology from behavior unless evidence supports the involvement of the student's views about knowledge. A critic could claim that, despite Miss Kagey's intentions, students' epistemologies were not involved. The cookie analogy, according to this criticism, "knocks" students into mechanistic reasoning without involving their views about knowledge.

We see evidence to the contrary. The cookie analogy isn't a "lesson" in generating mechanistic explanations. It's an illustration from everyday life of what kind of knowledge counts as an answer to "how" versus "why." For students to understand that illustration well enough to transfer it to an unfamiliar terrain, a scientific discussion of the leaf question, they must have already possessed some knowledge—perhaps tacit and context sensitive—about the differences between those two forms of knowledge.[8] Conversely, if students didn't have epistemological resources for understanding the difference between teleological and mechanistic knowledge, the cookie example would not have made sense to them as something relevant to explaining why leaves change color.

A skeptic could say Miss Kagey's intervention merely illustrated the difference between different kinds of explanations without tapping into students' epistemological views

[7]We suspect Sam read something about leaves with his parents. However, his answer is not the one biologists would give.

[8]A less plausible alternative, that Ms. Kagey's 1-minute intervention *taught* students a subtle epistemological distinction from scratch, also implicates knowledge about knowledge as contributing to students' changed behavior.

about which kinds of explanations "count" as knowledge in which contexts. By this account, students were merely "mimicking" the form of mechanistic explanation modeled by the teacher. If this were true, however, then more of the students could have begun mimicking that form after hearing the stomach analogy. The fact that students' behavior changed so dramatically only after they had heard an everyday, easily understood example of the difference between "knowing why" and "knowing how" suggests that Miss Kagey tapped into students' views about knowing.

Taking another tack, a critic could contend that epistemologies are by definition articulate and reflective, not the kind of thing that can be inferred from behavior unless supported by explicitly epistemological statements made by students. Because the resources framework allows for tacit epistemological knowledge elements, this line of reasoning rules out our framework by definition, not by investigation. As science teachers and education researchers, however, we are interested not just in the views about knowledge that students profess, but also in the views about knowledge that students actually use while learning science. If some of these cognitive elements turn out to be tacit, we think it's unproductive for "epistemology" researchers to define themselves out of the business of investigating these educationally relevant aspects of students' knowledge about knowledge.

## CONCLUSION

In this article, we argued that the resources framework for describing personal epistemologies can account for the core evidence that supports the developmental and beliefs frameworks, but not vice versa. Next, we applied the three frameworks to an explicitly epistemological third-grade science lesson. The developmental and beliefs frameworks do not make incorrect predictions. The trouble with those perspectives is that they have little to say. They don't provide a language for describing the teacher's intervention or for explaining why one of her interventions worked far better than did the others. The resources perspective, by contrast, provides a framework for describing the teacher's intervention as tapping into epistemological resources and for explaining the success of that intervention.

This conclusion has implications for research and instruction. The resources perspective may prove to be a productive framework in which to explore students' enacted epistemologies in the classroom and how those epistemologies affect their learning. Instead of giving surveys, researchers should use classroom observations, along with extended task-based clinical interviews, to gather finer grained data of students' context-sensitive views about knowledge.

For science teachers, our perspective provides a language for thinking and talking about the kinds of interventions many good teachers already use (and new teachers could learn to use), interventions in which the teacher taps into epistemological resources students have already developed but fail to apply in science class. This contrasts with a "conceptual change" model in which teachers confront and replace naïve epistemological beliefs.

## ACKNOWLEDGMENTS

This work was supported by the National Science Foundation, Award #ESI–9986846. Any opinions, findings, conclusions, or recommendations expressed are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

Belenky, M. F., Clinchy, B. M., Goldberger, N. R., & Tarule, J. M. (1986). *Women's ways of knowing: The development of self, voice, and mind*. New York: Basic Books.

Bell, P., & Linn, M. C. (2002). Beliefs about science: How does science instruction contribute. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 321–346). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28,* 235–252.

Crowley, K., & Siegler, R. S. (1999). Explanation and generalization in young children's strategy learning. *Child Development, 70,* 304–316.

diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2–3), 105–225.

diSessa, A. A., Elby, A., & Hammer, D. (2002). J's epistemological stance and strategies. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 237–290). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Feldman, D. H. (1994). *Beyond universals in cognitive development*. Norwood, NJ: Ablex.

Fischer, K. W. (1980). A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review, 87,* 477–531.

Fischer, K. W., & Pruyne, E. (2002). Reflective thinking in adulthood: Emergence, development, and variation. In J. Demick & C. Andreoletti (Eds.), *Handbook of adult development* (pp. 169–197). New York: Plenum.

Flavell, J. H. (1963). *The developmental psychology of Jean Piaget*. Princeton, NJ: Van Nostrand.

Hammer, D. M. (1994). Epistemological beliefs in introductory physics. *Cognition and Instruction, 12,* 151–183.

Hammer, D. M., & Elby, A. (2002). On the form of a personal epistemology. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 169–190). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

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

Hofer, B. K. (2001). Personal epistemology research: Implications for learning and teaching. *Educational Psychology Review, 13,* 353–383.

Hofer, B. K. (2002a). Epistemological world views of teachers: From beliefs to practice. *Issues in Education, 8,* 167–173.

Hofer, B. K. (2002b). Personal epistemology as a psychological and educational construct: An introduction. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 3–14). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research, 67,* 88–140.

Hogan, K. (1999). Relating students' personal frameworks for science learning to their cognition in collaborative contexts. *Science Education, 83,* 1–32.

Karmiloff-Smith, A. (1992). *Beyond modularity*. Cambridge, MA: MIT Press.

King, P. M., & Kitchener, K. S. (1994). *Developing reflective judgment: Understanding and promoting intellectual growth and critical thinking in adolescents and adults* (1st ed.). San Francisco: Jossey-Bass.

King, P., & Kitchener, K. S. (2004). Reflective judgment: Theory and research on the development of epistemic assumptions through adulthood. *Educational Psychologist, 39,* 5–18.

Kitchener, K. S. (1983). Cognition, metacognition and epistemic cognition. *Human Development, 26,* 222–232.

Kohlberg, L. (1981). *Essays on moral development* (1st ed.). San Francisco: Harper & Row.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96,* 674–689.

Kuhn, D. (1997). Constraints or guideposts? Developmental psychology and science education. *Review of Educational Research, 67,* 141–150.

Leach, J., Millar, R., Ryder, J., & Sere, M. G. (2000). Epistemological understanding in science learning: the consistency of representations across contexts. *Learning and Instruction, 10,* 497–527.

Linn, M. C., & Hsi, S. (2000). *Computers, teachers, peers*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Linn, M. C., & Songer, N. B. (1993). How do students make sense of science? *Merrill-Palmer Quarterly-Journal of Developmental Psychology, 39,* 47–73.

Lising, L. & Elby, A. (2003). *The impact of epistemology on learning: A case study from introductory physics.* Manuscript submitted for publication.

May, D. B., & Etkina, E. (2002). College physics students' epistemological self-reflection and its relationship to conceptual learning. *American Journal of Physics, 70,* 1249–1258.

Metz, K. E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research, 65,* 93–127.

Minsky, M. L. (1986). *Society of Mind*. New York: Simon & Schuster.

Perry, W. B. (1970). *Forms of intellectual and ethical development in the college years: A scheme*. New York: Holt, Rinehart & Winston.

Piaget, J., & National Froebel Foundation. (1967). *Further aspects of Piaget's work*. London: Routledge & Kegan Paul.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66,* 211–227.

Rest, J. R. (1979). *Development in judging moral issues*. Minneapolis: University of Minnesota Press.

Roth, W. M., & Roychoudhury, A. (1994). Physics students' epistemologies and views about knowing and learning. *Journal of Research in Science Teaching, 31,* 5–30.

Schommer, M. (1990). The effects of beliefs about the nature of knowledge in comprehension. *Journal of Educational Psychology, 82,* 498–504.

Schommer, M. (1993). Epistemological development and academic performance among secondary students. *Journal of Educational Psychology, 85,* 406–411.

Schommer, M., Crouse, A., & Rhodes, N. (1992). Epistemological beliefs and mathematical text comprehension: Believing it is simple does not make it so. *Journal of Educational Psychology, 84,* 435–443.

Schommer-Aikins, M. (2004). Explaining the epistemological belief system: Introducing the embedded systemic model and coordinated research approach. *Educational Psychologist, 39,* 19–29.

Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.

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.

Southerland, S., Abrams, E., Cummins, C. L., & Anzelmo, J. (2001). Understanding students' explanations of biological phenomena: Conceptual frameworks or p-prims. *Science Education, 85,* 328–348.

Tamir, P., & Zohar, A. (1991). Anthropomorphism and teleology in reasoning about biological phenomena. *Science Education, 75,* 57–67.

Tannen, D. (1993). *Framing in discourse*. New York: Oxford University Press.

Tobin, K., & McRobbie, C. (1997). Beliefs about the nature of science and the enacted science curriculum. *Science and Education, 6,* 355–371.

Tsai, C. C. (1999). "Laboratory exercises help me memorize the scientific truths": A study of eighth graders' scientific epistemological views and learning in laboratory activities. *Science Education, 83,* 654–674.

Zohar, A., & Ginossar, S. (1998). Lifting the taboo regarding teleology and anthropomorphism in biology education—heretical suggestions. *Science Education, 82*, 679–697.