Getting Started with Research on Epistemologies and Expectations

Andrew Elby

Department of Physics and Department of Curriculum & Instruction
University of Maryland, College Park
College Park, MD 20742

Abstract:

In this chapter, I introduce the notion of student epistemologies and expectations, their views about what counts as knowledge and learning in a given physics class and in physics more generally. I then review some of the ways in which researchers have studied these constructs and make suggestions about getting started on your own research. A major theme is that important theoretical questions about the cognitive structures and processes underlying student epistemologies — and how best to study them — are not yet settled. Researchers therefore need to try to uncover and articulate the theoretical assumptions implicit in their research methods.

1. An opening example: Why is Jan having trouble?

I'll introduce the notion of epistemology and expectations with a story that captures the idea better than a definition could. "Jan" and three other algebra-based physics students were working on the "Light and Shadows" tutorial created by the University of Washington Physics Education Group.[1] The students have light bulbs, a screen, and pieces of cardboard with holes of different shapes; see Fig. 1. Exploring different arrangements of bulbs and holes, the students observe and explain the bright spots on the screen. The tutorial guides students toward understanding that lights rays emanate from each glowing point on the filament; the rays head off in all directions, with each ray traveling in a straight line; and only rays passing through the hole in the cardboard contribute to the pattern on the screen.
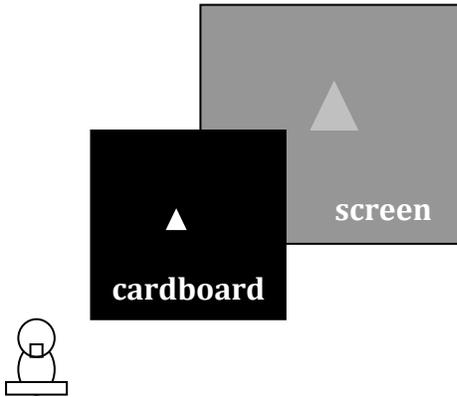
Figure 1. Students predict and explain the patterns that appear on the screen when the bulb shines light through the hole in the cardboard.

Early in the tutorial, the students notice that moving the bulb to the right makes the bright spot on the screen move to the left. While addressing the next worksheet question, "What do your observations suggest about the path taken by light from the bulb to the screen?" Jan searches for an explanation of what's happening. As you read through the following minute of conversation, documented by Lising and Elby,[2] pay particular attention to Jan.

> Nancy: How is it possible for the things to, like when we have the two bulbs, for one little circle to create the two . . .
>
> Veronica: Because they are two different directions. One's going in like that and one is going in like that [gestures show light approaching the hole from two different directions].
>
> Jan: So you are saying that . . .
>
> Nancy: But what's the normal direction of the light? Cause that's what I'm asking.

Veronica: It, it spans out, and whatever part goes through that circle is the part we're going to see.

Jan: [drawing as she talks] So the light is like that and these are the rays, and the vector points that way will go through the hole.

Nancy: Okay, so then if you move it up, then it's going to be?

Carl: So if here is the hole and the light is down here, the light is going to go in the direction …

Jan: Right, so like it has

[Nancy, Jan, and Carl talking, unintelligible]

Veronica: Really, it's just normal.

Jan: All the rays are going like this. So, it's kind of like polarized.

Veronica: Mmm, not really….It's just, well, it's just, guys you're making it, you're trying to make it more difficult. It's just, the light goes out. It only goes through that one circle. So, obviously, if it is down here, and I'm looking through that circle. Look, you're sitting down here. You're looking at this big cardboard. You're looking through that little circle. All you're going to see is what's up there. It's a direct line.

Jan: Look, I see what you're saying, alright. But, I'm just trying to make it like physics- physics-oriented. [laughs]

Veronica: It is, it is physics-oriented. That's just the way it is.

Jan: Alright.

Despite Jan's claim that she "sees what [Veronica is] saying," her tutorial homework showed minimal understanding of the targeted concepts. Yet, from multiple classroom observations and six hours of clinical interviews, we know Jan was a hard-working, mathematically adept student who did well in the course. So, *why is she having difficulty learning these optics concepts?* Before reading on, please come up with one or two plausible answers.

Traditionally, physics education researchers tend to explain student difficulties in two ways: (i) identifying a misconception that needs to be dislodged, or (ii) finding a gap in the student's knowledge or skills. Do these factors explain Jan's troubles? Well, she shows evidence of harboring misunderstandings about polarization and of not getting the idea that light spans out in all directions from its source. However, these conceptual difficulties cannot account for Jan's troubles *in this*

episode. Veronica convinces Jan that light goes out from the bulb at all angles, as evidenced by Jan's gestures during this conversation and by diagrams she drew on her homework. Furthermore, whatever misunderstandings she has about polarization do not account for why, on her homework, she couldn't use Veronica-style ray tracing to generate predictions and explanations about simple bulb-hole-screen scenarios. An understanding of polarization isn't needed to complete these tasks.

By analyzing Jan's statements in the classroom and during interviews, Lising & Elby [2] also ruled out other plausible explanations of Jan's troubles. During tutorials, she consistently took part in the conversations, as illustrated above. She worked hard on homework, so we can't chalk up her difficulties to lack of motivation or engagement. Furthermore, in interviews, she repeatedly showed the ability to generate and critique qualitative explanations of phenomena; she's not just a "plug 'n' chugger."

Jan's problem, as Veronica identified, is her *approach* to learning and understanding physics. After Jan brought up polarization, Veronica responded, "Mmm, not really…. *you're trying to make it more difficult*" (emphasis added). Veronica considers a good qualitative explanation to be sufficient: "It's just, the light goes out. It only goes through that one circle…" By contrast, Jan keeps trying to bring in technical terms like "vectors" and "polarized." She wants to recast Veronica's explanation to "make it like physics- physics-oriented." To her, an informal, qualitative explanation isn't "physics-oriented." Veronica disagrees: "It is, it is physics-oriented. That's just the way it is." The students here aren't arguing about a concept or an experimental result; they're arguing about what counts as a valid explanation — what counts as knowledge — in physics class. As Lising and Elby[2] argue, Jan fails to grapple with and thereby learn Veronica's common-sense ideas not because she is incapable, but because she views doing so as unrelated to gaining a formal "physics-oriented" understanding.

When I present the Jan-Veronica conversation at conferences, some physics educators offer misconceptions-based or skill-deficit-based explanations of Jan's behavior. Others see "I'm just trying to make it like physics- physics-oriented" as the crux of her difficulties. The first step toward getting started with epistemology/expectations research,

and I'll define those terms shortly, is learning to see what "game" a student is playing in physics class and how it affects her learning.

2. Introduction to epistemology and expectations

A student's physics *epistemology* is her set of views about the nature of knowledge, knowing, and learning in physics. *Expectations* are her views about what kinds of knowledge and learning are expected and rewarded in physics class or in schooling more generally. These constructs overlap, and whether you need to tease them apart depends on your research question. For now, I'll discuss them together.

2.1 Common epistemologies and expectations

This section, drawing mostly on work initiated by Hammer,[3,4] summarizes common student views about physics knowledge and learning.

2.1.1 Formulas vs. concepts

Students have different views about what physics knowledge is made of. Near the *formulas* end of this spectrum, students think that physics consists of facts and formulas, with the concepts serving as little more than cues for which equations to use. Near the *concepts* end, students think that the "stuff" of physics is concepts *expressible* in equations. Students holding the first view see equations as little more than problem-solving tools, while students holding the second view see physics equations as expressing meaning, as saying something about the world. Unsurprisingly, most introductory physics students come down closer to the *formulas* viewpoint.[3-5] Undoubtedly you've seen behavior reflecting that view.

An example from Hammer[3] illustrates the *concepts* end of the spectrum. Solving a homework problem during a clinical interview, "Tony" finds the angular momentum (with respect to a given axis) of an airplane flying in a straight line. The interviewer asks how something moving straight can have an *angular* velocity.

Tony: Here they're talking about instantaneously . . . . That's like when you sit there and watch a train come, you'll see it come, and it kind of sits there [when it's far away], and as it goes by, it zooms by . . . . The faster you turn your head, that's what the angular velocity is.

The ingenuity of Tony's explanation grabs our attention. The point I want to highlight, though, is that Tony thought such an explanation was possible and therefore engaged in the task of formulating one. By contrast, interview subjects exhibiting a *formulas*-based epistemology didn't view it as feasible and/or relevant to give common-sense explanations of this kind.

2.1.2 Pieces vs. coherence

Some students think physics knowledge consists of largely disconnected pieces (e.g., algorithms for different types of problems), while others expect physics to consist of interrelated ideas that fit into a coherent whole. As Hammer[3] discusses, students near the *pieces* end of the spectrum have reason to learn physics the same way they learn state capitals; memorize disconnected bits of information. Students exhibiting a *coherence* epistemological stance, by contrast, are prone to notice — and try to resolve — inconsistencies between ideas introduced in class, common sense, and everyday experiences.

Two interview subjects from Hammer [3] illustrate the distinction between *pieces* and *coherence* views. "Roger" was solving for the acceleration of the blocks in this modified Atwood's machine (Fig. 2). He found a sensible expression for the total force on the two-block system, $F = m_1g - m_2g\sin\theta$. However, he then set that force equal to the force on each individual block: $F = m_1a_1$ and $F = m_2a_2$. When he saw that this gave him a different acceleration for each block, he remarked that it seemed strange. But after checking his algebra and finding no mistakes, he said that he was "90% sure" he was right.   This reflected a pattern in Roger's work, of treating mathematical problem solving as separate from tangible sense-making.
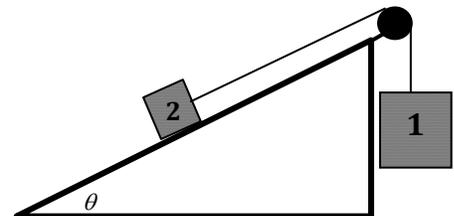

Figure 2. Modified Atwood's machine addressed in different ways by Roger and Tony

Tony, the student who offered the head-turning explanation of angular velocity, made the same mistake as Roger when he first tried the Atwood machine problem. But Tony immediately rejected the possibility that the blocks could have different accelerations. Pointing to his calculation, he explained that they "said the force is going to be … right here," indicating the smaller block, "and now I'm saying that's not true." He progressed quickly to a correct solution, writing $F = (m_1 + m_2)a$ and explaining that the force he calculated accelerates both blocks. Yet, Tony's mathematical manipulation skills were not evidently better than Roger's. Tony's success stemmed instead from his epistemological view that equations express conceptual content and that this content should make sense. Unlike Roger, he rejected a non-sensical answer for being non-sensical.

2.1.3 Transmissionist vs. constructivist

Some students view learning physics as absorbing knowledge from professors and textbooks, while others view learning as building up (constructing) their own understanding. (Hammer called this dimension Authority vs. Independence.) This distinction manifests itself, e.g., in how your students take and use notes: Some students write down every word you say and read through them again and again, while other students write down little but sometimes look at you or the board with a puzzled expression.

Instructors who implement tutorials or other forms of collaborative active learning often face student resistance arising, in part, from transmissionist views. Redish regularly documents this resistance in his algebra-based university physics class by inviting students to "free write" their impressions of the course during week 3 or 4.[6] Many students write that the professor should explain everything instead of making students think it out for themselves. (As the course continues, many students' views evolve.)

Interestingly, as Hammer[3] notes, some "transmissionist" students recognize that experts and talented students can make sense of the material for themselves, and understand it better as a result. In these cases, the students' views about learning are entangled with self-efficacy, their views about their own abilities.[2,7]

2.1.4 Innate vs. effort

As just mentioned, a student's views about the importance of natural ability vs. hard work interact with his epistemological views along the *transmissionist-constructivist* spectrum. Some students think their capacity to learn science or math mostly reflects innate ability. You've probably heard students say "I'm just not good at math" or "I'm more of a literature-type person." On the other end of the innate-effort spectrum, students think that hard work determines success. Although researchers argue about whether to call this set of views "epistemological,"[8] Dweck[7] and others have shown that students' views along this spectrum affect persistence and achievement. A few physics education researchers have touched on this spectrum,[4,9] but you should look elsewhere for deeper exploration of self-efficacy and intuitive theories of intelligence.[7,10,11]

2.2 When epistemologies and expectations diverge

So far, I've lumped epistemologies and expectations together. "Ellen" illustrates the distinction and why it can be important.[12] She was taking a fast-paced physics course inhabited largely by pre-meds. She entered the course with the constructivist expectation that she'd be able to make sense of the material in her own terms. Within a few weeks, however, she felt overwhelmed by the pace and discouraged by the superficial attention to concepts. To survive the homework and tests, she shifted her approach, focusing on rote application of algorithms rather than deeper conceptual understanding. But she hated this shift because she *knew* that she wasn't learning physics. In this way, Ellen's expectations diverged from her epistemology. Her epistemological views about what it means to understand physics remained constructivist. But her expectations became transmissionist: she saw the course as rewarding rote use of routines absorbed from authority. Although the split between Ellen's epistemology and expectations was unusually severe and articulate, some research shows this type of split to be commonplace.[13]

Your research interests should determine whether you lump epistemologies and expectations together or tease them apart. For example, if you're exploring whether a new curriculum alters

students' approach to your course, then you might lump epistemologies and expectations together, on the grounds that they work together in a student's mind to affect her study strategies.[4] By contrast, if you're studying how a physics course affects students' views of what scientists do, you'll need to tease apart course-specific expectations from epistemological views about what counts as knowing and knowledge in a discipline.

2.3 Section wrap-up

Previous research has identified categories of views students have about physics knowledge and learning.[3,4,14,15] Unsurprisingly, the less sophisticated views are common, and traditional physics instruction leaves students' views largely unchanged.[3,4] More surprisingly, even in courses that employ collaborative active learning, where students achieve large *conceptual* gains, *epistemological* gains are minimal or nonexistent.[4]   Epistemological gains have sometimes been documented when the instructor made it a primary instructional goal suffusing the curriculum.[6,9,16]

The research discussed above describes student epistemologies in terms of broad categories, e.g., the student sees knowledge as coherent or as piecemeal. In my view, a potential growth area for PER on epistemology is the pursuit of more detailed accounts of students' epistemological views and causal accounts of how those views affect students' in-the-moment behavior while learning physics.

3. Theoretical frameworks for studying epistemologies and expectations

Since research methods always encode explicit or tacit assumptions about the thing being studied, I need to discuss some competing theoretical frameworks used to describe student epistemologies. This debate is about cognitive structures, the units of thought that students bring to bear when reasoning and learning. Very briefly, some researchers assume that students' epistemologies take the form of robust, stable beliefs — or even theories — that reliably guide the students' thinking across multiple contexts.   Other researchers

assume that students' views about knowledge and learning are more fluid and context-dependent.

To make this distinction clear and concrete, I'll introduce it not with regard to students' epistemologies but with regard to their preconceptions about the physical world — an area of students' thinking you probably encounter regularly. Once I've clarified the relevant distinctions in this familiar setting, I'll show how they apply to student epistemologies and expectations. By wrestling with these competing theoretical perspectives, you can ensure that the theoretical assumptions encoded in your research methods are ones you consciously choose rather than ones you tacitly back into.

3.1 Introduction to the beliefs vs. knowledge in pieces debate

Consider this standard conceptual question used by physics teachers and education researchers: After a ball gets thrown straight up, what forces act upon it as it rises? Many students say that, in addition to the downward force from gravity, the ball also feels an upward force "from the throw," a force that decreases in strength as the ball loses speed. Similarly, for a ball rolling along the floor, some students say it experiences a force along its direction of motion. What can we infer from this (and similar) data about students' preconceptions?

Some researchers infer that students possess a full-fledged *theory* of forces and motion. For instance, McCloskey[17] argues that students hold an impetus theory similar to the pre-Newtonian theory held by medieval natural philosophers. By this account, students are expected to give impetus-theory-driven responses to a wide range of questions.

Other researchers question whether students' preconceptions show the coherence and robustness of a *theory*. They believe instead that students possess *(mis)conceptions* about the physical world.[18,19] These researchers interpret the above data as evidence for the misconception *motion implies force*, the idea that an object in motion must experience a force acting along its direction of motion. In the (mis)conceptions framework, (mis)conceptions are assumed to be stable and robust elements of students' thinking, applied across a wide range of contexts.

Still other researchers assume that conceptual reasoning exhibits more context-dependence than the theory or (mis)conceptions frameworks imply.   According to the "knowledge-in-pieces" or "resources" perspective, students possess a wide range of intuitive ideas and other cognitive resources for reasoning about the world, abstracted from their experiences.[20,21] These cognitive resources do not generally correspond to formal physics concepts. For example, the intuitive idea that *things keep doing what they're doing* might help students understand why a bell sounds for a long time after it's struck, or why an object in motion stays in motion. That same intuitive idea, however, could also lead students to think that a marble shot out of a semicircular tube continues tracing a circular arc. So, an intuitive idea like *things keep doing what they're doing* is neither right nor wrong. It can contribute to both correct reasoning (about the bell) and incorrect reasoning (about the marble). By contrast, an intuitive theory or a (mis)conception is either right or wrong.

To illustrate another feature of the resources framework, I need to introduce another intuitive idea students may possess, sometimes called *maintaining agency*.[20,22]   This is the idea that an effect is maintained only so long as its cause remains active. A student with this intuitive idea activated in his mind might think that a light bulb quickly loses brightness when the electricity gets shut off, or that a ball thrown upward keeps rising only as long as the "force from the throw" remains active.

So *maintaining agency*, like *things keep doing what they're doing* illustrates that a resource can contribute to both productive and unproductive reasoning. Another feature of resources is that they turn on and turn off in response to changes in context. To see what I mean, consider this question: What forces act on the upward-thrown ball at its peak? According to impetus theory, or according to the misconception *motion requires force*, or according to the intuitive idea of *maintaining agency*, the ball no longer experiences an upward force at its peak; the force gradually declines to zero as the ball slows down and stops. But many students who attribute a declining upward force to the rising ball say that, at the peak, an upward force balances the downward pull of gravity.[20,23]   Resources theorists explain this inconsistency as follows: While the rising ball triggers an intuitive sense of maintained agency — the ball must continue to feel an

upward force in order to keep moving upward — the motionless ball at its peak triggers an intuitive sense of balance.[20] This intuitive sense of balance leads the student to attribute balancing forces. *Maintaining agency* is inactive in this reasoning.

(Mis)conceptions theorists, by contrast, explain students' inconsistent answers in terms of shifts between correct and incorrect conceptions during the process of conceptual change,[19] and theory theorists can attribute these student responses to "glitches" in their reasoning. My point here is to underscore the context dependence of students' intuitive ideas, according to resources theorists, even for students not undergoing conceptual change. Different scenarios trigger different combinations of conceptual resources, and hence students' reasoning isn't always expected to show consistency across different contexts.

Crucially, however, the resources framework does not imply complete fragmentation and incoherence in students' reasoning. A set of cognitive resources can be mutually reinforced by each other and/or by contextual cues, leading to a locally coherent pattern of thought.[24] For example, to explain the somewhat consistent pattern of thought that McCloskey[25] attributed to students' holding an impetus theory, diSessa[26] modeled students' reasoning as "a local confluence of about a half-dozen [intuitive ideas] adapted to a particular class of situations."[27] Resources theorists expect, however, that many scenarios would trigger different sets of resources. In other words, according to resources advocates, the "local confluence" of intuitive ideas is a local coherence in students' thinking, not a global coherence.

Although I am a partisan in the debate among the theory, (mis)conceptions, and resources theoretical frameworks, I've tried to present each fairly. The theory and (mis)conceptions frameworks are simple and clear, and they offer parsimonious explanations of frequently-observed, well-documented patterns of student reasoning. They are the dominant frameworks used in science education research. The resources framework offers messier cognitive models to explain those patterns, but is well-suited to explain context-dependent shifts in students' conceptual reasoning.

Now that I've reviewed three frameworks for describing students' preconceptions about the physical world — theories,

(mis)conceptions, and resources — I can discuss how these frameworks have been used to describe students' epistemologies.

3.2 Epistemologies/expectations as stages or theories

The earliest researchers of students' epistemological views,[28,29] and a large percentage of current researchers,[8] employ a version of the theories framework. They describe students' epistemological stances as consisting of coherent theories or stages. Some researchers assume, with experimental support, that students gradually progress from lower to higher stages of epistemological sophistication.[30] A few researchers working within this framework have studied students of physical science.[31] Most PER on student epistemologies has adopted one of the perspectives described below.

3.3 Epistemologies/expectations as beliefs

Studying students learning math, Schommer[10,32] introduced the idea that students' epistemologies consist of beliefs along different dimensions, such as whether knowledge is simple (disconnected pieces) or complex (interconnected) and whether it's certain or tentative. These epistemological beliefs resemble the (mis)conceptions attributed by (mis)conceptions theorists: they're comparatively robust, stable, context-independent elements of a student's thinking. Adopting this theoretical stance, a physics education researcher might interpret the epistemological spectra discussed above — formulas vs. concepts, pieces vs. coherence, transmissionist vs. constructivist, etc. — as dimensions along which a student has a belief. Interestingly, Hammer,[3] who first documented most of these dimensions in detail, was agnostic about whether his subjects' epistemological consistency stemmed from a general *belief* or from a local coherence in the context of the students' physics course. Some subsequent physics epistemology researchers have adopted that agnosticism.[4] Others have argued that the consistency of students' survey responses within certain *empirically determined* clusters of questions indicates that students have coherent "consistent ideas," i.e., beliefs.[14]

3.4 Epistemologies/expectations as context-dependent local coherences

Some recent work argues that student epistemologies are best described by a resources framework, according to which a student might shift between different "beliefs" in response to contextual cues.[24,33] For example, Rosenberg, Hammer and Phelan[34] documented a group of eighth-grade earth science students shifting from one belief-like epistemological coherence, the view that knowledge generation is fact accumulation, to anther epistemological coherence, the view that knowledge generation is constructing causal stories. Just as diSessa [26] models students' "impetus-theory" reasoning as the locally coherent activation of certain intuitive ideas about the world, Hammer and colleagues model students' epistemological stances as the locally coherent activation of epistemological resources, students' intuitive ideas *about knowledge and learning*.

In summary, student epistemologies can be conceptualized as theories/stages, as beliefs, or as locally coherent activations of resources.   I'm highlighting the differences between these perspectives for a reason: your explicit or tacit choice of theoretical frameworks will influence your research questions and also your research methods and interpretations of data.   I'll point out these subtleties as they arise in the next section.

4. Common methods for studying epistemologies and expectations

In this section, I discuss some ways in which researchers have studied students' epistemologies and expectations.   I've tried to avoid rehashing material from Otero & Harlow's article on qualitative methods[35] and Engelhardt's article on survey construction[36] from the first volume of *Getting Started in PER*.   Instead, I emphasize issues of interpretation that are particularly important to research on epistemologies.   Although I'll organize the discussion by data collection methods, I'll use previous research to illustrate data analysis methods.

4.1 Surveys

Perhaps the most common way of studying epistemologies/expectations, both inside and outside the PER community, is via surveys given to large numbers of students.

4.1.1 Common surveys, common uses

In PER, the most commonly cited surveys are probably

- The Colorado Learning Attitudes about Science Survey (CLASS), probing a mix of epistemologies, expectations, confidence, and interest along empirically-determined dimensions. See http://www.colorado.edu/sei/class/[14]
- The Maryland Physics Expectations Survey (MPEX, revised into MPEX II),[4] probing epistemologies/expectations along the epistemological dimensions introduced by Hammer.[3] See http://umdperg.pbworks.com/MPEX-II
- The Views About Science Survey (VASS), probing epistemologies and expectations as well as students' views about the nature of science and scientific theories, and the relevance of science in students' lives. See http://cresmet.asu.edu/prods/vass.shtml[37]
- The Epistemological Beliefs Assessment for Physical Science (EBAPS), probing epistemologies and expectations. See http://www2.physics.umd.edu/~elby/EBAPS/home.htm[9]

Physics education researchers commonly evaluate whether a course affected students' views by giving the same survey as a pre- and post-test and looking for changes. Outside of PER (and sometimes inside PER), researchers often use epistemology surveys to explore connections between epistemological sophistication and other factors such as academic achievement or ability to comprehend a textbook-style passage about statistics.[32] Adams et al.[14] also express optimism that a valid, reliable survey could "characterize an individual student in a useful way."

4.1.2 Theory-ladenness of survey interpretation

How you use a survey, and how you interpret the results, depends on the theoretical framework you tacitly or explicitly adopt for describing epistemologies and expectations. For example, consider the issue just raised, of whether a survey can usefully characterize an

individual student. If you think a student's epistemology consists of stable, robust, comparatively context-independent theories or beliefs, then a sufficiently well-crafted survey can indeed reveal a student's "epistemological profile" in some detail. By contrast, resources theorists worry that a student's consistent survey responses could reflect a local coherence attached to the context of *reflecting* on knowledge and learning. The reflective context might elicit more consistent, more sophisticated epistemological views than those triggered when the student actually engages in learning physics. Furthermore, resources theorists expect that different classroom contexts, such as listening to a lecture vs. working with other students on a conceptual tutorial, might trigger different sets of epistemological resources. For these reasons, resources theorists use surveys to obtain a crude read-out of the epistemological state of a class (taking into account the idiosyncrasies of the survey-taking context), but not to uncover the epistemology of an individual student.

Of course, particularly sophisticated and particularly unsophisticated students are likely to show consistency across multiple classroom and survey contexts, in which case beliefs and resources advocates can agree that the survey characterizes the individual student fairly well. Adams et al.[14] observed this phenomenon: "for several notable students (both good and bad) we have retrospectively looked at their individual survey results, and these were quite consistent with the highly expert or highly novice behavior these students indicated in their work and discussions with faculty." For middle-of-the-road students, though, beliefs and resources advocates disagree about how usefully a survey can characterize the individual student.

Theoretical considerations also influence what counts as a "reliable" survey. To see why, suppose first that the beliefs framework is correct, and hence a student has a set of robust beliefs. In that case, a survey reliably uncovers those beliefs only if (i) the epistemological dimensions probed by the survey correspond to the beliefs held by the student, and (ii) the items probing a given dimension yield highly correlated answers.   Standard survey-construction techniques incorporate versions of (i) or (ii): Factor analysis or some other cluster analysis is used to determine (or confirm) the dimensions along which students' beliefs lie.[36] If two survey questions probing the same dimension elicit contradictory student responses, then at

least one of those questions is deemed invalid/unreliable and therefore revised or omitted. After the survey is iteratively refined in this manner, it is deemed "reliable" for revealing students' beliefs.

Resources theorists have a messier view of reliability. They worry that the "factors" revealed by factor analysis might be local coherences sensitive to the reflective nature of the survey context and to the particular questions asked on the survey. Furthermore, from the resources perspective, two items probing the same dimension might elicit different student responses not because one of the questions is invalid or unreliable, but rather, because of real context dependence in the student's epistemology. For instance, a student might express more constructivist tendencies when thinking about group work than when thinking about lecture. In that case, omitting from the survey the question about group work or the question about lecture would increase "reliability" only by sweeping under the rug some context dependence in the students' views about learning. Alternatively, letting those two items get placed in different factors would obscure the fact that the two items show the student to have inconsistent, context-dependent views *about the same epistemological issue*.

Despite these nuances, researchers of all theoretical stripes emphasize the importance of validation interviews for survey questions. In a validation interview, the subject thinks aloud while answering (or reviewing his previous answers to) survey questions. The researcher can then see if the subject interprets the questions as intended and if the subject's answer stems from the targeted aspects of the subject's cognition. For example, in a survey I co-developed, one question initially read, *Often, a scientific principle or theory just doesn't make sense. In those cases, you have to accept it and move on.* I thought that a subject's agreement with this statement would mean he didn't expect the principles he was learning to make sense. However, several subjects who agreed with the statement told me that, when they first encounter a hard new concept in a fast-paced class, they often "accept it and move on" but later go back later and try to make sense of it. For those students, agreement with the italicized statement indicated adaptive survival skills, not an expectation of non-sensicality, so that item as written was invalid. Here's the rewritten version: *Often, a scientific principle or theory just doesn't*

make sense. In those cases, you have to accept it and move on, because not everything in science is supposed to make sense. Students who defer their sense-making until later would still disagree with the statement.

In short, the relative ease with which surveys can be administered, scored, and statistically analyzed masks subtle issues of interpretation. I urge new physics education researchers to make explicit, for themselves and others, the often tacit assumptions that accompany claims about survey results. For example, what does it mean that my high school students showed significant gains in their MPEX and EBAPS scores between the beginning and the end of the school year?[9] I'd love to think it reflects a stable, globally-applicable increase in epistemological sophistication!   However, that's a defensible inference only if the students possess stable, robust, comparatively context-independent beliefs about physics knowledge and learning. However, the beliefs expressed on the surveys might not be robust enough to drive behavior: without independent evidence from their classroom behaviors, I don't know whether the changes in their survey responses reflect changes in how they learn physics. Maybe the survey responses correspond to a local coherence; perhaps my students learned to switch on a certain set of epistemological resources *in my class.* In other classes, other sets of resources might get triggered. In any case, almost all researchers would agree that surveys alone cannot provide a *complete* epistemological snapshot of a student or a class.

4.2 Interviews

Interviews are arguably the backbone of epistemology research. Early researchers of student epistemologies used interviews almost exclusively,[29] and survey developers typically design their surveys around insights gleaned from interviews.[4] Audio- or videotaping an interview, downloading the data to computer, transcribing, and even captioning the original videotape have become straightforward. (Audiotaping has the advantage of being less intrusive, while videotaping captures the gestures and facial expression of the subject, which can inform your interpretations.) In this section, I'll discuss some ways in which interviews can be administered and analyzed, but I'll only scratch the surface.

4.2.1 Different styles of interview

Interviews designed to tease out students' epistemologies and expectations take many forms. Some examples will illustrate what I mean by "style" and show the diversity of styles available.

Hammer[3] was testing whether university students displayed consistent epistemological stances *in the context of their introductory physics course*. He was also looking for causal connections between their epistemologies and their learning. So, over six sessions with each subject, he tried to keep the various tasks closely connected to the students' experiences in their physics course. However, to make sure any consistency he observed wasn't just an artifact of the task structure, he employed a mix of tasks, including general questions ("How is your course going?"), explanation tasks ("How would you explain this equation you've used, $v = v_0 + at$, to a friend?"), and problem solving (having students think aloud while solving homework problems). Pursuing indications of students' epistemologies, Hammer improvised frequently. After completing the interviews, he performed qualitative analysis of, for instance, how "Roger" and "Tony" approached problem solving and other tasks (see the Atwood examples above). He also coded epistemological indications in students' responses, and thereby showed that each subject displayed consistent "beliefs" within the formulas-concepts, pieces-coherence, and transmissionist-constructivist spectra.

The semi-structured (i.e., partly improvisational) nature of Hammer's interviews deserves special attention. I'll illustrate this kind of improvisation with a simple made-up example. In response to "How is the course going?" a student complains that homework problems are too hard. You ask what makes them hard. The student says it's difficult to figure out which formula to use. You ask if figuring out which formula to use is part of every problem? How important a part? Are there other parts? The ensuing conversation about the student's approach to problem solving, perhaps as a search for equations, could give insight into the student's epistemology along the *formulas vs. concepts* dimension.

Kitchener & King's[30,38] interviews differ from Hammer's in structure and content. They engage subjects in *reflective judgment* about knowledge *in the context of unsettled or controversial issues* such as the safety of food additives or the origin of humans (creationism vs. evolution). Their single-session interviews are quite structured, focused on drawing out subjects' views about the source, reliability, and justification for the knowledge under discussion. They explore the content and consistency of subjects' epistemologies by coding responses into one of seven stages of epistemological development. They found that subjects are epistemologically consistent not just within but also across topic areas (e.g., food safety vs. origins of humans), and that over time subjects progress through the stages in the predicted order (though not everyone reaches the highest levels).

A third example of interview style: Lising and Elby[2] interviewed Jan, the student who wanted a more "physics-oriented" explanation of light and shadows, to test a specific hypothesis. We thought that, far removed from physics class, she would display an epistemological stance more friendly toward everyday, common-sense reasoning about physical phenomena. So, we held the six interviews with her in the education rather than the physics building, with the interviewer introduced as an education researcher. The interviews consisted mostly of problem-solving tasks. Although Jan readily engaged in intuitive/everyday reasoning to address questions she spontaneously identified as physics problems, partly confirming our hypothesis, she appeared to treat such reasoning as disconnected from more formal, mathematical reasoning, in which she also engaged. To explore our new, emergent hypothesis that Jan had an epistemological "wall" between everyday/intuitive and formal reasoning in physics, we focused part of our analysis on instances in which Jan used both formal and everyday/intuitive reasoning to address the same question, and we coded for the extent to which the two types of reasoning informed or otherwise "spoke" to each other in her reasoning. In this way, we produced evidence that the hypothesized epistemological wall does indeed constrain Jan's reasoning. Using qualitative discourse analysis, we then argued that this wall helps to explain Jan's behavior in the "Light and Shadows" tutorial and also in another tutorial we videotaped.

These examples illustrate different interview styles. Interview structures range from fairly standardized scripts to open-ended exploration of students' ideas. Interview tasks range from fairly direct (though contextualized) questions about how the subject is treating/justifying knowledge to problem-solving tasks to explanation tasks. Interview time frames range from a single session to six or more sessions.

The methods of analyzing the interview data show similar diversity. Based on pilot studies, Hammer had formulated three epistemological dimensions. His codes enabled him to test whether students were epistemologically consistent within each dimension, while qualitative analysis of selected interview segments illustrated and supported his epistemological "diagnoses" of his subjects. King and Kitchener use quantitative analysis only, coding subjects' answers based on indicators iteratively developed in a careful way over many years. Lising and Elby began with qualitative discourse analysis of classroom data, then used similar analysis of the interview data and, from that, formulated a hypothesis and corresponding coding scheme for quantitative analysis. So, Lising & Elby's coding scheme was emergent, designed to probe a particular aspect of Jan's epistemology, to make well-supported claims about that one student.

4.2.2 Effect of theoretical assumptions on interview-based research

Of course, the interviewer's theoretical assumptions influence each stage of the research, but the influence can be nearly invisible. Getting started in this field, it's essential to try to explicate the tacit assumptions underlying what you're doing. I'll illustrate this process using the research discussed above.

Hammer was agnostic between the beliefs and resources frameworks. Taking the resources perspective seriously, he entertained the possibility that fine-grained changes in task or subject matter — using an equation to solve a problem vs. explaining the equation to someone else, solving a physics problem vs. reflecting on how the physics course is going — could affect the student's in-the-moment epistemological stance. So, to create a fair test of whether students were epistemologically consistent within the "macrocontext" of their physics course, Hammer varied the "microcontext," in this case the

tasks and the subject matter. In this way, Hammer could argue that his subjects' epistemological consistency in the context of their physics class was not simply an artifact of the interview protocol.

The resources framework also helped to motivate Hammer's emphasis on eliciting spontaneous indications of students' epistemologies as they solved problems, complained about the course, and so on. He rarely asked direct epistemological questions, and only in response to an idea the student had brought up. Undoubtedly, asking direct questions like "how do you decide whether to believe [that equation]?" would have produced a higher density of epistemological codings. However, the resources perspective allows the possibility that the epistemological resources students bring to bear when asked about the source and justification of knowledge — an abstract topic students rarely think about explicitly, especially in a traditionally-taught physics class — might differ from the epistemological resources activated while they're solving a physics problem or shooting the breeze about their class. Hammer's decision to code for students' epistemologies as they engaged in authentic physics tasks and conversations about physics class stemmed in part from his theoretical stance that epistemologies might not consist of well-articulated, context-insensitive beliefs.

Lising and Elby's exploration of Jan stemmed directly from our commitment to a resources perspective: seeing Jan display a certain epistemological stance in physics class, we wanted to explore the possibility that she might display a different stance in a less "physics-oriented" context. Although we found that she took different epistemological stances in the classroom versus the interviews, our research (ironically) ended up focusing on an element of her epistemology that was consistent across the two contexts.

King and Kitchener view epistemologies as consisting of stages. Their main evidence is that (i) subjects show epistemological consistency across multiple reflective judgment interviews addressing different controversial topics, and (ii) when followed over many years, subjects progress through the epistemological stages in the predicted order. As a resources advocate, however, I worry that the reflective judgment interview itself induces, rather than uncovers, much of the observed consistency: Subjects surely view the interviews as a

context in which to be thoughtful, and "looking good" in such a context involves striving for consistency in one's answers — "sticking to your story." The epistemological stances subjects display in other contexts — watching a political debate, taking a class — might show more variability. Furthermore, I've critiqued King & Kitchener's coding scheme for ignoring contextual nuance in subjects' answers that should influence whether the answer is coded as more or less sophisticated.[39]

The admittedly obvious point here is that your tacit or explicit theoretical leanings influence your research questions, data collection, and data analysis and interpretation. To be fair, I should turn the tables on myself. A theories/stages advocate might worry that Lising and Elby, immersed in attention to contextual nuance, fail to ask questions or collect data in a way that might lead to more generalizable conclusions. A theories/stages advocate might also worry that all this attention to context makes us miss broad epistemological patterns that capture much of students' behavior, or that our analysis "sees" contextual nuance where there is merely noise.

Any theoretical perspective has strengths but also produces "blind spots" in the researcher's inquiry. To minimize this narrowed vision, you can become well-versed in the different perspectives and you can discuss your work-in-progress with people from different perspectives.

4.2.3 Interpreting interview data: The role of social dynamics

Experienced interviewers, especially those taking a situated cognition perspective,[40] emphasize an issue I've ignored so far, the role of power dynamics and other social dynamics in influencing the interview subject's behavior. For example, a woman interviewed by a man might consciously or unconsciously avoid reasoning in ways that are negatively stereotyped as feminine. Some interview subjects consciously or unconsciously try to figure out what the interviewer "wants to hear."

An example: during her problem-solving interviews with me, Jan used qualitative reasoning more than quantitative reasoning. Her

statements and questions eventually made it clear, however, that she had picked up on cues I was sending — she knew I was particularly interested in her qualitative reasoning. This realization didn't challenge our arguments about the epistemological stances she took when engaged in qualitative reasoning, or about her ability to use everyday/intuitive reasoning to address physics problems. However, we cannot claim that qualitative reasoning is her "natural choice" outside the physics building. The interview dynamics played a role in her choice.

Needless to say, researchers must attend to these concerns, while conducting the interview and while analyzing the data afterward. Looking at the videotape itself, not just at the transcription, provides valuable clues about the subject's state of mind: body language, tone of voice, gestures, nervous vs. hearty laughter, and so on.[41]

4.3 Observations and artifacts

An "artifact" is a physical record of thought and behavior, such as students' homework or exam responses. Everyone agrees that a student's cognition during an interview or survey differs, at least in some ways, from her cognition during classroom-related activities. For this reason, to explore the epistemologies and expectations that most influence students' learning behavior, some researchers rely partly or largely on classroom observations and artifacts.[2,42,43]

4.3.1 Behavior ≠ epistemology: Methodological challenges of observations

Authentic classroom data carries a methodological danger, however: You can't just "read off" epistemologies or expectations from behavior. Let me give an example. Suppose you videotape a physics student over many class sections. During group work, she is typically disengaged, and her questions center around "what's the right answer?" During lecture, she is alert, frantically writing down everything the instructor says. From these observations, we might infer that she has transmissionist view of learning (in physics, at least), or perhaps transmissionist expectations about what the tests reward. It's possible, however, that she's disengaged during group work because she's shy, or because she dislikes her group, or because the ideas her group bats around aren't substantive. Maybe she takes

notes not to memorize but to serve as a starting point for sense-making that she prefers to do on her own. Before concluding that she has transmissionist views, we would need evidence casting doubt on those alternative explanations. Such evidence could come from interviews or surveys. It could also come from statements she makes in class, such as Jan's request for a more "physics-oriented" explanation in response to Veronica's qualitative discussion of optics phenomena.[2]

Partly because of these methodological issues, many epistemology researchers who use observations or artifacts also use interviews. Hogan,[42] for example, used interviews to study students' views about the nature of science and also their views about their own knowing and learning. The views students enacted during collaborative learning correlate strongly with the views they expressed in interviews about their own learning but not to their views about the nature of science.

In some cases, epistemologies expressed in interviews clash with classroom behavior. For example, research on K-12 teachers has found that some (but not all!) teachers express constructivist views in interviews but enact transmissionist views while teaching.[44]

May & Etkina[45] made clever use of an epistemologically-rich artifact: journals in which college physics students reflected upon their own learning. May and Etkina developed a coding scheme for epistemological sophistication, based on explicit epistemological comments and also on how the student talked about her own learning. Students who exhibited more sophisticated epistemologies in their journals achieved greater conceptual gains in the course, as independently measured by conceptual surveys.

Observation-based research on physics students' epistemologies have relied mostly on video of students working in groups on tutorials, labs, or homework.[46] The key, of course, is for the students to be *talking*.

5. Getting started with your own research

In this section, I'll draw upon my own experiences and observations to offer advice about getting started in epistemology research.

5.1 Start with a research question or issue, not a method

It's fairly common in PER for someone to hear or read about a cool survey and excitedly decide to give it to his own students. There's nothing wrong with that, of course, and the results can be interesting. But sometimes the survey, despite its appeal, doesn't really get at what you want to know. In my view, although a cool survey or interview protocol should definitely inspire you, it's worth taking the time to articulate to yourself what your interest really is, what you're fired up to explore. Then you can fine tune your research methods accordingly. And to refine your questions and methods, I recommend that you…

5.2 Start with small N observations/interviews

It's tempting and common to jump into giving a large-N survey to "get at" your research question, but taking the time to conduct relevant observations and interviews can help you refine your research question and formulate more valid and interesting survey questions to suit your particular purpose.

For instance, in recent work at the University of Maryland, we've been exploring why engineering majors in an upper division circuits course often resist mathematical sense-making, by which we mean translating back and forth between mathematical formalism and conceptions/observations about the real world. The MPEX II survey we'd used in previous projects probes this issue. But a student's off-hand comment during discussion section alerted us to a possible disconnect students may perceive between the types of reasoning they think "belong" in an engineering class and the types of reasoning used by professional engineers. We modified an interview protocol to get at this issue and piloted it on another student. The revised protocol enabled us to find an unexpected epistemological idea, that the conceptual reasoning emphasized in some homework applies only to overly idealized circuits, not at all to real-world circuits. We subsequently probed for this idea with a modified version of MPEX II.

My point is that if we had just gone ahead and used the unmodified MPEX II, we might have missed this issue.

5.3 Look outside the PER literature

To get background knowledge and ideas, don't restrict yourself to PER. Depending on your particular interests, other relevant pockets of literature might include

- the math education literature on students' beliefs[47] and on teachers' beliefs[48] about knowing and learning mathematics.
- the education psychology literature on "personal epistemologies"[8,49] and on students' and teachers' views about the nature of science,[50] and the relation between epistemologies, study strategies, and academic performance, in math and science and more widely.[32,51]
- parts of the science education literature on K-12 students' and teachers' beliefs.[43,52]

6. Conclusion

The field of students' and teachers' epistemologies/expectations is both growing and unsettled: increasing numbers of researchers are using an increasing variety of methods and theoretical perspectives to study it. A better understanding of students' and teachers' views about knowledge and learning, and deeper causal accounts of the interactions among epistemologies/expectations, learning behaviors, and learning outcomes will not only help researchers construct better models of cognition but will also help instructors devise better ways to help their students learn.

References

[1]   L. C. McDermott, P. S. Shaffer, and Physics Education Group, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River, NJ, 2002).
[2]   L. Lising and A. Elby, "The Impact of Epistemology on Learning: A Case Study in Introductory Physics," Am. J. Phys. **73** (4), 372-382 (2005).

3   D. M. Hammer, "Epistemological Beliefs in Introductory Physics," Cog. and Instruc. **12** (2), 151-183 (1994).

4   E. F. Redish, J. M. Saul, and R. N. Steinberg, "Student Expectations in Introductory Physics," Am. J. Phys. **66** (3), 212-224 (1998).

5   D. M. Hammer, "Students' Beliefs About Conceptual Knowledge in Introductory Physics," Int. J. Sci. Ed. **16** (4), 385-403 (1994).

6   E. F. Redish and D. M. Hammer, "A Large Lecture Course That Produces Epistemological Change," Am. J. Phys. **77** (7), 629-642 (2009).

7   C. S. Dweck and J. Bempechat, "Children's Theories of Intelligence: Consequences for Learning.," in *Learning and Motivation in the Classroom*, edited by S. G. Paris, G. M. Olson, and H. W. Stevenson (Erlbaum, Hillsdale, NJ, 1983), pp. 239-256.

8   B. K. Hofer and P. R. Pintrich, "The Development of Epistemological Theories: Beliefs About Knowledge and Knowing and Their Relation to Learning," Rev. Ed. Res. **67** (1), 88-140 (1997).

9   A. Elby, "Helping Physics Students Learn How to Learn," Am. J. Phys. **69** (7 SUPP1), S54-S64 (2001).

10   M. Schommer, "The Effects of Beliefs About the Nature of Knowledge in Comprehension," J. Educ. Psych. **82** (3), 498 - 504 (1990).

11   M. Schommer, "Epistemological Development and Academic Performance Among Secondary Students," J. Educ. Psych. **85** (3), 406-411 (1993); F. Pajares, "Self-Efficacy Beliefs in Academic Settings," Rev. Ed. Res. **66** (4), 543-578 (1996).

12   D. M. Hammer, "Two Approaches to Learning Physics," Phys. Teacher **27** (9), 664-670 (1989).

13   A. Elby, "Another Reason that Physics Students Learn by Rote," Am. J. Phys.. PER Supplement **67** (7 SUPP1), S52-S57 (1999).

14   W. K. Adams, K. K. Perkins, N. Podolefsky, N. D. Finkelstein, and C. E. Wieman, "A New Instrument for Measuring Student Beliefs About Physics and Learning Physics: The Colorado Learning Attitudes about Science Survey," Phys. Rev. Spec. Top.: PER **2** (1), 010101 (2006).

15   W. M. Roth and A. Roychoudhury, "Physics Students Epistemologies and Views about Knowing and Learning," J. Res. Sci. Teach. **31** (1), 5-30 (1994).

16   V. K. Otero and K. E. Gray, "Attitudinal Gains Across Multiple Universities Using the Physics and Everyday Thinking Curriculum," Phys. Rev. Spec. Top.: PER **4** (2008).

17   M. McCloskey, "Intuitive Physics," Sci. Am. **249,** 122 (1983).

18   K. A. Strike and G. J. Posner, "A Conceptual Change View of Learning and Understanding," in *Cognitive Structure and Conceptual Change*, edited by L. H. T. West and A. L. Pines (Academic Press, New York, 1985), pp. 211-231.

19   R. K. Thornton, "Conceptual Dynamics: Changing Student Views of Force and Motion," in *Thinking Physics for Teaching*, edited by C. Tarsitani, C. Bernardini, and M. Vincentini (Plenum Publishing, London, 1995); R. K. Thornton, presented at the International Conference on Undergraduate Physics Education, 1997 (unpublished).

20   A. A. diSessa, "Towards an Epistemology of Physics," Cog. and Instruc. **10** (2-3), 105-225 (1993).

21   D. M. Hammer, "Student Resources for Learning Introductory Physics," Am. J. Phys., PER Supplement **68** (S1), S52-59 (2000); J. Smith, A. diSessa, and J. Roschelle, "Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition," J. Learn. Sci. **3** (2), 115-163 (1993/1994).

22   D. M. Hammer, "More than Misconceptions: Multiple Perspectives on Student Knowledge and Reasoning, and an Appropriate Role for Education Research," Am. J. Phys. **64** (10), 1316-1325 (1996).

23   A. A. diSessa, A. Elby, and D. M. Hammer, "J's Epistemological Stance and Strategies," in *Intentional Conceptual Change*, edited by G. M. Sinatra and P. R. Pintrich (Lawrence Erlbaum, Mahwah, NJ, 2002), pp. 237-290.

24   D. M. Hammer, A. Elby, R. E. Scherr, and E. F. Redish, "Resources, Framing, and Transfer," in *Transfer of Learning From a Modern Multidisciplinary Perspective*, edited by J. Mestre (Information Age Publishing, Greenwich, CT, 2005), pp. 89-120.

25   M. McCloskey, "Naive Theories of Motion.," in *Mental Models*, edited by D. Gentner and A. Stevens (Lawrence Erlbaum, Hillsdale, NJ, 1983), pp. 299-324; M. McCloskey and R. Kargon, "The Meaning and Use of Historical Models in the Study of Intuitive Physics," in *Ontogeny, Phylogeny, and Historical*

Development, edited by S. Strauss (Ablex, Norwood, NJ, 1988), pp. 49-67.

26   A. A. diSessa, "What do 'Just Plain Folk' Know About Physics?" in *Handbook of Education and Human Development: New Models of Learning, Teaching, and Schooling*, edited by D. R. Olson and N. Torrance (Blackwell Publishers, Oxford, 1996), pp. 709-730.

27   A. A. diSessa, N. Gillespie, and J. B. Esterly, "Coherence Versus Fragmentation in the Development of the Concept of Force," Cog. Sci. **28** (6), 843-900 (2004).

28   M. F. Belenky, B. M. Clinchy, N. R. Goldberger, and J. M. Tarule, *Women's Ways of Knowing: The Development of Self, Voice, and Mind* (Basic Books, New York, 1986); W. B. Perry, *Forms of Intellectual and Ethical Development in the College Years: A Scheme* (Holt, Rinehart, and Winston, New York, 1970).

29   K. S. Kitchener and P. M. King, "Reflective Judgment: Concepts of Justification and Their Relationship to Age and Education," J. App. Dev. Psych. **2**, 89-116 (1981).

30   K.S. Kitchener, P.M. King, P .K. Wood, and M. L. Davison, "Sequentiality and Consistency in the Development of Reflective Judgment: A Six-year Longitudinal Study," J. App. Dev. Psych. **10**, 73-95 (1989).

31   M. C. Linn and N. B. Songer, "How do Students Make Sense of Science?" M-P. Qtly.- J. of Dev. Psych. **39** (1), 47-73 (1993).

32   M. Schommer, A. Crouse, and N. Rhodes, "Epistemological Beliefs and Mathematical Text Comprehension: Believing it is Simple Does not Make it So," J. Educ. Psych. **84**, 435-443 (1992).

33   A. Elby and D. M. Hammer, "Epistemological Resources and Framing: A Cognitive Framework for Helping Teachers Interpret and Respond to Their Students' Epistemologies," in *Personal Epistemology in the Classroom: Theory, Research, and Implications for Practice*, edited by L. D. Bendixen and F. C Feucht (Cambridge University Press, Cambridge, UK, 2010); L. Louca, A. Elby, D. M. Hammer, and T. Kagey, "Epistemological Resources: Applying a New Epistemological Framework to Science Instruction," Ed. Psych. **39** (1), 57-68 (2004).

34   S. A. Rosenberg, D. M. Hammer, and J. Phelan, "Multiple Epistemological Coherences in an Eighth-grade Discussion of the Rock Cycle," J. Learn. Sci. **15** (2), 261-292 (2006).

35   V. K. Otero and D. B. Harlow, "Getting Started in Qualitative Physics Education Research," in *Getting Started in PER*, edited by C. Henderson and K. A. Harper (Amer. Assoc. of Physics Teachers, College Park, MD, 2009), Vol. 1.

36   P. V. Engelhardt, "An Introduction to Classical Test Theory as Applied to Conceptual Multiple-choice Tests," in *Getting Started in Physics Education Research*, edited by C. Henderson and K. A. Harper (Amer. Assoc. of Physics Teachers, College Park, MD, 2009), Vol. 1.

37   I. Halloun and D. Hestenes, "Interpreting VASS Dimensions and Profiles," Sci. & Ed. **7** (6), 553-577 (1998).

38   P. M. King and K. S. Kitchener, "The Reflective Judgment Model: Twenty Years of Research on Epistemic Cognition," in *Personal Epistemology: The Psychology of Beliefs about Knowledge and Knowing*, edited by B. K. Hofer and P. R. Pintrich (Erlbaum, Mahwah, NJ, 2002), pp. 37-61.

39   A. Elby and D. M. Hammer, "On the Substance of a Sophisticated Epistemology," Sci. Ed. **85**, 554-567 (2001).

40   J. S. Brown, A. Collins, and P. Duguid, "Situated Cognition and the Culture of Learning," Ed. Res. **18** (1), 32-42 (1989); L. Bannon and S. Bodker, "Beyond the Interface: Encountering Artifacts in use," in *Designing Interaction: Psychology and the Human-computer Interface*, edited by J. M. Carroll (Cambridge University Press, Cambridge, 1991), pp. 227-253.

41   D. Tannen, *Framing in Discourse* (Oxford University Press, New York, 1993); D. Tannen, "What's in a Frame? Surface Evidence for Underlying Expectations," in *Framing in Discourse*, edited by D. Tannen (Oxford University Press, New York, 1993), pp. 14-56.

42   K. Hogan, "Relating Students' Personal Frameworks for Science Learning to Their Cognition in Collaborative Contexts," Sci. Ed. **83** (1), 1-32 (1999).

43   C. L. Smith, D. Maclin, C. Houghton, and M. G. Hennessey, "Sixth-grade Students' Epistemologies of Science: The Impact of School Science Experiences on Epistemological Development," Cog. and Instruc. **18** (3), 349-422 (2000).

44   L. A. Bryan, "Nestedness of Beliefs: Examining a Prospective Elementary Teacher's Belief System About Science Teaching and Learning," J. Res. Sci. Teach. **40** (9), 835-868 (2003); K. King, L. Shumow, and S. Lietz, "Science Education in an Urban

Elementary School: Case Studies of Teacher Beliefs and Classroom Practices," Sci. Ed. **85** (2), 89-110 (2001); P. E. Simmons, A. Emory, T. Carter, T. Coker, B. Finnegan, D. Crockett, L. Richardson, R. Yager, J. Craven, J. Tillotson, H. Brunkhorst, M. Twiest, K. Hossain, J. Gallagher, D. Duggan-Haas, J. Parker, F. Cajas, Q. Alshannag, S. McGlamery, J. Krockover, P. Adams, B. Spector, T. LaPorta, B. James, K. Rearden, and K. Labuda, "Beginning Teachers: Beliefs and Classroom Actions," J. Res. Sci. Teach. **36** (8), 930-954 (1999).

45   D. B. May and E. Etkina, "College Physics Students' Epistemological Self-reflection and its Relationship to Conceptual Learning," Am. J. Phys. **70** (12), 1249-1258 (2002).

46   T. Bing, A. Gupta, and E. F. Redish, "Different Types of Mathematical Justification in Upper Level Physics," in American Association of Physics Teachers (Greensboro, NC, 2007); R. E. Scherr and D. M. Hammer, "Student Behavior and Epistemological Framing: Examples From Collaborative Active-learning Activities in Physics," Cog. and Instruc. **27** (2), 147-174 (2009).

47   A. Schoenfeld, "When Good Teaching Leads to Bad Results: Disasters of Well Taught Mathematics Classes," in *Learning Mathematics From Instruction*, edited by T.P. Carpenter and P. L. Peterson (1988), Vol. 23, pp. 145; E Yackel and P. Cobb, "Sociomathematical Norms, Argumentation, and Autonomy in Mathematics," J. for Res. in Math. Ed. **27**, 458-477 (1996).

48   D. K. Cohen, "A Revolution in One Classroom: The Case of Mrs. Oublier," Ed. Eval. and Pol. Analys. **12** (3), 327-345 (1990); N. M Speer, "Connecting Beliefs and Practices: A Fine-Grained Analysis of a College Mathematics Teacher's Collections of Beliefs and Their Relationship to His Instructional Practices " Cog. and Instruc. **26** (2), 218-267 (2008).

49   B. K. Hofer and P. R. Pintrich (eds), *Personal Epistemology: The Psychology of Beliefs about Knowledge and Knowing* (Lawrence Erlbaum, Mahwah, N.J., 2002); K. R. Muis, L. D. Bendixen, and F. C. Haerle, "Domain-Generality and Domain-Specificity in Personal Epistemology Research: Philosophical and Empirical Reflections in the Development of a Theoretical Framework," Ed. Psych. Rev. **18** (1), 3-54 (2006); M. Schommer, C. Calvert, G. Gariglietti, and A. Bajaj, "The Development of Epistemological

Beliefs Among Secondary Students: A Longitudinal Study," J. Educ. Psych. **89** (1), 37-40 (1997).

50   R. Driver, J. Leach, R. Millar, and P. Scott, *Young People's Images of Science* (Open University Press, Buckingham, UK, 1996); L. M. Lederman, "Teachers' Understanding of the Nature of Science and Classroom Practice: Factors that Facilitate or Impede the Relationship," J. Res. Sci. Teach. **36** (8), 916-929 (1999); N. G. Lederman, "Students' and Teachers' Conceptions of the Nature of Science: A Review of the Research," J. Res. Sci. Teach. **29** (1992).

51   M. Schommer, "Epistemological Development and Academic-Performance Among Secondary Students," J. Educ. Psych. **85** (3), 406-411 (1993).

52   E. A. Davis, "Untangling Dimensions of Middle School Students' Beliefs About Scientific Knowledge and Science Learning," Int. J. Sci. Ed. **25** (4), 439-468 (2003); N. B. Songer and M. C. Linn, "How do Students' Views of Science Influence Knowledge Integration?," in *Students' Models and Epistemologies of Science,* a special issue of J. Res. Sci. Teach., edited by M. C. Linn, N. B. Songer, and E. L. Lewis **28**, pp. 761-784 (1991); K. Tobin and C. McRobbie, "Beliefs About the Nature of Science and the Enacted Science Curriculum," Sci. and Ed. **6** (4), 355-371 (1997); W. A. Sandoval and K. Morrison, "High School Students' Ideas About Theories and Theory Change After a Biological Inquiry Unit," J. Res. Sci. Teach. **40** (4), 369-392 (2003).