Tapping epistemological resources for learning physics[1]

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ABSTRACT

Research on personal epistemologies has begun to consider ontology: Do naive epistemologies take the form of stable, unitary beliefs or of fine-grained, context-sensitive resources? Debates such as this regarding subtleties of cognitive theory, however, may be difficult to connect to everyday instructional practice. Our purpose in this article is to make that connection. We first review reasons for supporting the latter account, of naive epistemologies as made up of fine-grained, context-sensitive resources; as part of this argument we note that familiar strategies and curricula tacitly ascribe epistemological resources to students. We then present several strategies designed more explicitly to help students tap those resources for learning introductory physics. Finally, we reflect on this work as an example of interplay between two modes of inquiry into student thinking, that of instruction and that of formal research on learning.

STUDENT EPISTEMOLOGIES

An extensive body of research addresses beliefs about knowledge and learning, or "epistemological beliefs" (Hofer & Pintrich, 1997), with much of this work focused on epistemologies in physical science (Carey & Smith, 1993; Elby, 1999; Gunstone, 1992; Halloun, 1998; Hammer, 1994a; Hewson, 1985; Linn & Songer, 1993; Redish, Steinberg, & Saul, 1998; Roth & Roychoudhury, 1994; Smith, Maclin, Houghton, & Hennessey, 2000). This research has provided evidence of an epistemological component to students' success in learning introductory physics. Students who have difficulties often view physics knowledge as a collection of facts, formulas, and problem solving methods, mostly disconnected from everyday thinking, and they view learning as primarily a matter of memorization. By contrast, successful learners tend to see physics as a coherent system of ideas, the formalism as a means for expressing and working with those ideas, and learning as a matter of reconstructing and refining one's current understanding.

Researchers' recognition of the existence of student epistemologies and the need to address them in instruction represents substantial progress. For teachers, the identification of epistemology as a category of informal knowledge provides an alternative interpretive lens for understanding students' ideas and behavior, assessing abilities and needs, and adapting plans and strategies (Hammer, 1995). In some respects, however, instructional strategies have long been ahead of theoretical development.

Just as conceptual change researchers have generally described students' prior knowledge as consisting largely of stable, robust *misconceptions* that cannot contribute to expert understanding, epistemology researchers have mostly described naive epistemologies in terms of stable, counter-productive beliefs that must be replaced in order to achieve sophistication. As Smith, diSessa and Roschelle (1993/1994) argued regarding misconceptions, this view provides no account of the raw materials from which students may construct more productive epistemologies (Hammer & Elby, 2002).

A more nuanced understanding of student epistemologies, however, is embedded in much instructional practice. Instead of viewing students' intuitive epistemologies as entirely unproductive, teachers and curriculum developers often assume, implicitly, that students already possess productive epistemological resources that can be triggered by effective instruction. For example, when a software environment prompts students to distinguish "explanations" from "observations," it reflects an assumption that they have the cognitive resources—perhaps underdeveloped—to do so. Observations of students responding to such prompts (Linn & Hsi, 2000), confirms the reasonableness of this assumption.

We first review an account of naive epistemologies as made up from fine-grained, context-sensitive resources, rather than as stable, context-general beliefs. We then discuss the instructional significance of this difference, beginning in the following section with examples of familiar strategies and curricula that, we suggest, tacitly ascribe productive resources to students. In subsequent sections we describe strategies informed more deliberately by a resources framework, to illustrate how teachers who attribute context-sensitive resources to their students may invoke different strategies than teachers who ascribe context-general beliefs. Finally, we reflect on this work as an example of the interplay between two modes of inquiry into student thinking, that of instruction and that of formal research on learning.

THE FORM OF STUDENT EPISTEMOLOGIES

Research has provided evidence for the existence and importance of student epistemologies, but it has made less progress addressing their form. In this section, we explicate the distinction between understanding naive epistemologies in terms of stable, context-general beliefs and understanding them in terms of fine-grained, context-sensitive resources. For an expanded presentation of these arguments, see Hammer & Elby (2002).

Misbeliefs

Just as research on conceptual understanding has assumed naive physics to be made up of "misconceptions" (e.g. "force causes motion") that differ from expert conceptions ("force causes acceleration"), research on epistemologies has understood students to have "misbeliefs" ("knowledge is certain") that differ from expert beliefs ("knowledge is tentative"). On this view, developing a more sophisticated epistemology requires forming new beliefs, just as developing more sophisticated domain knowledge requires forming new conceptions (Strike & Posner, 1985).

This misconceptions/misbeliefs framework presents a number of difficulties. First, by describing only cognitive constructs that differ from experts', it offers no account of how students construct a more sophisticated understanding out of their prior knowledge (Smith et al., 1993/1994). Second, just as evidence from interview protocols (diSessa, 1993; Tytler, 1998) suggests naive reasoning in physics is not generally consistent in the manner a misconceptions account implies, there is evidence of inconsistency in student epistemologies, across disciplinary domains (Hofer, 2000; Stodolsky, Salk, & Glaessner, 1991) and across contexts within a given domain (Leach, Millar, Ryder, & Séré, 1999; Roth & Roychoudhury, 1994).

A manifold ontology of resources

These considerations suggest that an adequate model should be comprised, at least in part, of fine-grained epistemological resources, analogous to diSessa's (1993) phenomenological primitives ("p-prims") in intuitive physics. On this view, a naive epistemology draws on these resources, activating them—sometimes appropriately, sometimes not—in a manner that is sensitive to context.

For example, many students appear to view scientific knowledge as coming from authority. Still, even small children have epistemological resources for understanding knowledge as invented ("How do you know your doll's name is Ann?" "I made it up!") or knowledge as inferred ("How do you know I have a present for you?" "I saw you hide something under your coat."). Naive epistemologies may be made up of a collection of resources, each activated and appropriate in familiar contexts. To illustrate, the following are examples pertaining to the source of knowledge.

- *Knowledge as propagated stuff*: Invoking this resource means treating knowledge as a kind of stuff that can be passed from a source to a recipient. This stuff is not conserved: the source does not lose any knowledge by passing it. In this sense, knowledge is like fire, or sickness, or even "cooties." Children can understand the question "How do you know we're having soup for dinner" and respond "Because Mommy told me."
- *Knowledge as free creation*: Invention is a common experience for children, and "I made it up" a routine explanation for the origin of many ideas, including stories, imaginary characters, and games. Like the pictures a child draws on a blank page, knowledge by this resource does not have any source other than the child's mind, where it arises spontaneously.[2]
- *Knowledge as fabricated stuff*: Children may also think of knowledge as inferred or developed from other knowledge. Thus, the answer to "How do you know?" is "I figured it out from [the source material]." With this resource invoked, one would expect that others who have access to the same source material could generate the same knowledge. By contrast, knowledge by *Free creation* must be divulged by the creator.

Of course, the set of epistemological resources in anyone's repertoire must be much larger than these few examples. Furthermore, an adequate account would need to describe resources not only for understanding sources of knowledge, but also for understanding epistemological activities (e.g. *Accumulation*, *Formation*, *Checking*), forms (*Story*, *Rule*, *Fact*, *Game*) and stances (*Acceptance*, *Understanding*, *Puzzlement*).

Naming epistemological resources such as *checking*, we should note that this account connects with research on metacognition (Brown, Bransford, Ferrara, & Campione, 1983; Gunstone, 1992; Schoenfeld, 1983; Schoenfeld, 1992;

White & Frederiksen, 1998). When solving complex problems, capable math students invoke metacognitive strategies for checking their work and monitoring their progress (Schoenfeld, 1983, 1992). We distinguish as *epistemological* the resources by which students recognize checking and monitoring as activities in which they can engage, distinct from the cognitive machinery for engaging in them (Kitchener, 1983). For instance, a teacher may ask "What are you doing" to a student in the process of checking her reasoning. A response such as "I'm seeing if I messed up" or "I'm seeing if this makes sense" would reflect the epistemological resource *checking*; the student not only checks her knowledge, but understands herself to be doing so. For our present purposes, we take it as established by previous work that epistemologies are involved in learning, and we build our account from there. Thus, epistemological resources may serve the role of helping to activate metacognitive resources; or they may turn on in response to metacognitive activity, to play an administrative role.[3]

With respect to introductory physics, research cited above shows that students learn more successfully when they understand physics knowledge as a coherent system of ideas, the formalism as a means for expressing and working with those ideas, and the task of learning as a matter of reconstructing and refining one's current understanding. To interpret these results from a resources framework, the more successful learners do not necessarily have coherent, committed, articulate epistemologies (although some may). Their statements and behavior can be understood instead as reflecting the activation of productive resources in the context of the physics course. In other words, the "scientific epistemology" that a student seems to hold in physics class can be seen as arising not from a coherent system of beliefs about scientific knowledge, but rather, from the context-sensitive activation of a cluster of resources drawn from her personal epistemology.

A resources perspective also suggests that students who view learning physics as absorbing information from authority, for example, are likely to have more productive epistemological resources that they activate in other contexts. Rather than assume these students hold an incorrect theory that knowledge is received from teachers and texts, one may suppose they are applying *knowledge as propagated stuff* when *knowledge as fabricated stuff* would be more productive. In other words, despite the fact that in other contexts these students try to figure out new things from knowledge they already have, in physics class they look to receive information from the teacher.

Again, we have not developed any more than the bare beginnings of a list of such resources. However, as we discuss below, the general ontology of this view — the form it ascribes to student epistemologies — suggests different approaches to instruction than does the view that students hold epistemological theories. Our purpose here is to pursue the implications of this general shift in ontology, not of the particular examples we have described.

Instructional practices

A resources-based view of naive epistemologies suggests that instruction should help students find and activate epistemological resources productive for their learning, resources they already possess but apply only in other contexts. This strategy contrasts with the familiar conceptualization of instruction as needing first to elicit and expose counter-productive knowledge, then to confront and refute that knowledge, and finally to offer new ideas for students to adopt in its place (Strike & Posner, 1985).

From a resources perspective, there may not be any stable, counter-productive "beliefs" to elicit and confront. We are not saying that a resources view rules out the possibility of stable knowledge: In some cases, the activation of a set of resources may be robust, in which case elicitation and confrontation may be an appropriate strategy. Our point is that, in a resources framework, naive epistemologies need not be stable and robust in this way. Moreover, students have other resources available from which to construct a more appropriate epistemological stance. Instruction should help students find and apply those resources.

This sense seem inherent in existing pedagogical practice, as effective instruction can often be understood as helping students find and apply to a new context the productive resources they already have. A standard example comes from the realm of conceptual (as opposed to epistemological) resources. Minstrell's (1982) curriculum helps students draw on their sense of springiness to understand the passive force exerted by a table on a book. This sense of springiness is a conceptual resource students naturally invoke in some contexts (think of standing on a trampoline) but not in others (think of standing on a cement floor). Minstrell introduced intermediate contexts as a means of helping to students draw a connection (think of a cement floor "giving" like an extremely stiff trampoline), so that they apply their “springiness” resources to a new context, the book sitting on the table. Clement and his colleagues elaborated upon this strategy in terms of "bridging analogies" and "anchoring conceptions" (Clement, Brown, & Zeitsman, 1989).[4]

More often, the expectation of resources is tacit. Hewitt's popular textbook (Hewitt, 1985) contains numerous examples of instructional strategies that consist, in essence, of efforts to tap the conceptual resources students naturally activate in one context to help their thinking in another. For example, his explanations of Newton's Third Law[5] include an appeal to intuitions about "touching" or "contact" that have a similar symmetry: If object A touches object B, object B must touch object A.

The Minstrell and Hewitt examples reflect expectations of conceptual resources. Teachers also expect epistemological resources. For example, teachers often encourage students to see problem-solving as intellectual "exercise," drawing the analogy to physical exercise. This invites students to activate, in a learning context, resources they already invoke in understanding the benefits of practice, effort, and diligence in developing athletic ability. For another example, teachers often have students compare a scientific debate to a courtroom trial. Inherent in this strategy, again, is the expectation that students have productive resources for understanding argumentation, evidence, and subtleties of establishing “truth,” resources they likely activate in the context of a trial and that may be brought to bear on scientific inquiry.

Examples within computational learning environments include “notebook” tools (Linn & Hsi, 2000; Reiser et al., 2001) that provide distinct representational structures for data and observations, hypotheses and questions, and principles and explanations. Within each of the different areas are "prompts," such as "Our predictions are that . . . " or "We are wondering about. . ." Because the effectiveness of a prompt depends on its triggering productive knowledge and abilities, these designs assume that students have epistemological and other resources for getting started. Specifically, students must have a sense of what a *prediction* is, as an epistemological form, and of what *wondering* entails, as an activity.

As these examples illustrate, instructors and curriculum developers often presume students have productive epistemological resources, but they rarely discuss this explicitly. The question "What productive resources might students have that we could help them apply?" is generally embedded within questions of instructional practice: "What instructional moves or tools may promote effective learning?" In our view, research on epistemologies has yet to reflect the depth of insight inherent in teachers' and curriculum developers' strategies and designs.

Just as theorists can benefit from the insights embedded in instructional practice, instructional practice can benefit from theoretical progress. Studies have shown elementary school-age children to be capable of greater sophistication than educators have described (Metz, 1995; Samarapungavan, 1992). Curricula designed with these higher expectations in mind have provided compelling evidence to confirm them. Moreover, identifying specific areas of proficiency provides substantial leverage in designing instruction. For example, children have expertise for understanding and engaging in tasks of construction — children build things. This involves coordinating a variety of what others have called "epistemic games" (Collins & Ferguson, 1993; Perkins, in press), such as copying an existing design or inventing one's own, comparing for differences, and checking for errors. Educators have recognized this area of child expertise and sought to tap it in the service of science learning (diSessa, 2000; Harel & Papert, 1991; Hmelo, Holton, & Kolodner, 2000; Papert, 1980; Penner, Lehrer, & Schauble, 1998).

Epistemological resources for introductory physics

What children have accomplished in elementary schools suggests that they have epistemological resources for learning science, that they can build from these resources, and that by sixth grade they are capable of forming fairly sophisticated epistemological commitments with respect to science and science learning (Smith et al., 2000). Unfortunately, as the research cited above documents, high school and college students do not generally show such sophistication in introductory physics courses. Few older students have had the benefit of high-quality science education in elementary school. Even if they did, they might not import into their content-driven high school classes the clusters of productive resources they used in inquiry-driven elementary school science.

Undoubtedly, some high school and college students have formed robust yet counter-productive epistemological commitments with respect to school science. In these cases, teachers might find it useful to expose and confront those commitments, that is to treat them as stable misbeliefs. By contrast, many students' epistemologies may be quite unstable and varying with context, in which case the expose-and-confront strategies would not be appropriate. More important, regardless of the stability of their counter-productive epistemologies, all students must have productive resources, and much of the challenge for instruction is helping students find and activate them.

If previous work is correct that students learn more effectively when they see physics as coherent, the formalism as expressing ideas and reasoning, and learning as a matter of refining one's current understanding, then what are resources from which students might develop that epistemology? Our aim is to identify specific areas of expertise relevant to learning physics, to devise strategies that help students draw on that expertise, and to refine our understanding of its nature toward a more specific account of epistemological resources.

Students, for example, almost certainly have resources for understanding *rule systems*, such sports and games. Playing basketball or cards, and taking the game seriously, students would understand the need to resolve any ambiguities or inconsistencies they encounter in the rules. Here, then, is an area of expertise that may apply to understanding physics as a coherent system of ideas, instruction may help students apply that expertise by presenting physics in terms of "games" (Hestenes, 1992; Wells, Hestenes, & Swackhamer, 1995). Similarly, students have abundant informal experience working with representations and representational systems, and this expertise may profitably apply to more formal practices in science (diSessa, Hammer, Sherin, & Kolpakowski, 1991). We noted another locus of expertise above: Students' skill at construction suggests that they also have resources for understanding the activities of checking, repairing, and refining.

We do not, however, expect that the task of identifying students' epistemological expertise belongs exclusively to education research. Rather, we believe progress will come from fluid conversation between instructional practice and research on learning. As physics teachers and researchers, we often find ourselves having this conversation as we navigate back and forth between our own practices. Although research on learning has informed our teaching (Elby, 2001; Hammer, 1997), the influence has gone in the other direction just as strongly. Particularly in developing ideas about epistemological resources, we constantly find ourselves mining for insights embedded in instructional practice. In this respect as in others, the development of educational theory should be supported by teachers' expertise (Hammer & Schifter, 2001).

The remainder of this paper discusses the design of instructional strategies that have both informed and been informed by a resources view of epistemologies. The following section describes a course, "How to Learn Physics," that departs substantially from conventional introductory curricula with an intense, prolonged focus on epistemology. The subsequent section describes instructional strategies that target epistemological resources within the constraints of a more conventional curriculum. Throughout, we hope to make clear two common threads. First, in designing instruction and in deciding how to respond to students' reasoning, much of our thinking consists of trying to identify contexts of relevant, everyday epistemological expertise and, from there, of trying to help students apply that expertise to learning physics. (Of course, there are many other considerations as well, but we will concentrate on this one.) Second, instruction based on a resources view of naive epistemologies differs from instruction based on a beliefs/theories view. The debate about the form of students' epistemologies isn't just abstract theorizing; it bears on instructional practices.

"HOW TO LEARN PHYSICS"

We begin with *How to Learn Physics* (HTLP), an elective, off-track course one of us (David) designed and advertises "for people who might be interested in physics but are a little mystified or intimidated." It runs in seminar style, with brief lectures that focus primarily on epistemological topics rather than on what is traditionally understood as "content." The course aims to help students understand and approach learning science as a "refinement of everyday thinking,"[6] with the first lectures introducing a vocabulary to help them become more aware of everyday thinking, and subsequent lectures addressing refinement toward scientific understanding.

Of course, a student cannot learn how to learn physics without learning some physics, any more than someone could learn how to write poetry without writing some poetry. HTLP students study forces and motion, this choice of topic based on the richness and immediacy of students' intuitive knowledge about mechanical phenomena as well as on the historical and conceptual centrality of mechanics in the field of physics. It is an objective that students come to a basic comprehension of Newtonian principles, to recognize the coherence they afford for understanding wide domains of experience, and to develop habits of monitoring and revising their thinking for consistency with those principles. It is not an objective, however, that students become fluent Newtonian technicians.

Class meetings consist mostly of discussions, debates, and experiments, the experiments mostly informal and involving everyday objects. At several points in the semester there are brief reading assignments, drawn primarily from Galileo's Dialogues (Galilei, 1962/1632; 1991/1638). Written assignments consist of "essays sets," each with two problems; students write first drafts and then revisions based on comments from fellow students and David.

The first assignment introduces a three-part structure for essays that becomes standard throughout the course:

> For each problem, write an essay to explain at least two different ways of thinking that could lead you to different answers. In particular, explain:
>
> A) what you think the answer is and why;
>
> B) what you or someone else might be tempted to think is the answer and why;
>
> AND
>
> C) what you think is wrong with the reasoning in part B?
>
> In other words, write an argument, a counter-argument, and a response to the counter-argument. The response is the hardest part: Don't just repeat your first argument; *respond* to the reasoning in the counter-argument. One great way to do that is to come up with a situation in which the counter-argument would be correct, and explain why that situation is different from the one described in the question. ("That reasoning would work fine if _________, but in this case __________.")

By the end of the course, David leaves it unstated that an essay should address and coordinate multiple points of view. Students complete one assignment each week.

We turn now to a summary of the instructional objectives and the corresponding flow of the curriculum. This we present in three sections, following the syllabus of HTLP:

1) Developing an awareness of everyday thinking;
2) Learning to refine everyday thinking;
3) Developing and committing to a principled framework.

Each section describes the epistemological objectives of that part of the course, and equally important, the contexts of everyday epistemological expertise from which we try to draw productive resources. In this way, we emphasize how HTLP reflects a resources-based view of student epistemologies.

Developing an awareness of everyday thinking

The first lectures introduce a vocabulary, "Hidden assumptions" and "Shopping for ideas," to help students become more aware of their current, mostly tacit knowledge about physical phenomena, and to cultivate expectations that learning physics involves searching within and examining that knowledge.

A "hidden assumption" is "something you accept as true, at least for a moment, without realizing you're accepting it as true." From everyday life, students are likely to have resources for understanding this epistemological idea, that hidden assumptions can have a dramatic affect on their thinking. In the course, an old riddle serves as an early example:

> A boy and his father were in a car accident. The boy was injured, and the father was killed. At the hospital, the surgeon assigned to the boy took a look at him and exclaimed, "This is my son!" How could the boy be the surgeon's son if the boy's father had been killed in the crash?

What made this a riddle was a hidden assumption: *Surgeons are male*. People who are lulled unawares into making that assumption are stumped; those who are aware of the assumption are free to consider and reject it.

Other examples, some of which bear directly on physics, include cases when the hidden assumption is valid: You can drop-kick a football but not a bowling ball; a cup of water-color paint will eventually be used up (although it is hard to see any loss from a single use); an oven mitt keeps your hand cool when you hold a hot plate (or warm when you hold an ice tray); and so on.

These discussions introduce students to the notion that learning physics requires identifying hidden assumptions, examining them, and trying to understand when they apply and when they do not. "Shopping for ideas" is the course's name for the activity of searching within one's own knowledge and experience. The shopping metaphor is one connection to everyday experience that may help frame the task. Other connections can be more directly epistemological:

> Imagine you have met a new person and there's something about him that bothers you, but you can't quite put your finger on what it is. So you think about it, trying to figure out whether he reminds you of someone or you've met him before. You "shop" in your mind, through different sections of your knowledge and experience. You ask "Have I met him before?" and you try out different possibilities: "Have I seen him at the pool? At the store? In art class?" Or "Whom does he remind me of?" again, trying out some possibilities: "Uncle Ralph? Cousin George? Neighbor Charlie?" Eventually you may realize that he looks and sounds a bit like a character in a movie you saw recently. Having figured that out, you know that it's not really this new guy who troubles you but that movie character, and you don't have to worry about it any more. Or, if you were to realize that you've met him before and had an unpleasant interaction, you'd have found that feeling of irritation is warranted.

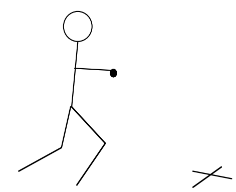
Because students are likely to understand this everyday phenomenon of knowledge, it provides an anchor for a bridging analogy, an epistemological version of Minstrell's and Clement's strategy described above (Clement et al., 1989; Minstrell, 1982). In this case, social situation serves as an epistemological anchor to help students understand the phenomenon of having a physical intuition, the source of which can be found by introspection:

> You need to do something like this in learning physics. Very often you'll have a sense that a ball or some other object ought to move in a certain way, but you'll have trouble putting your finger on why you

have that sense. Sometimes when you identify it you'll realize you're using an intuition that doesn't apply in this case, and you don't have to worry about it; sometimes you'll find you have an experience that's relevant and useful. In either case, it's important to try to figure out where these ideas come from.

For example, on their first problem set, students encounter the "running drop":

If you're running along, holding a quarter (or a set of car keys, or whatever you like!), and you want to drop it so that it hits a target on the floor, should you drop the quarter before you reach the target, when the quarter is directly over the target, or after you've passed the target?



A variety of possible hidden assumptions emerge in discussions and essays:

- your hand moves the quarter (so it doesn't have any motion of its own and stops when you let go);
- "carrying and dropping" is the same as "throwing" (so the quarter keeps moving when you drop it just as it would if you had thrown it);
- motion forward causes a force backward (so the quarter will move backward when you release it).

Each of these assumptions works well in some context. For instance, when carrying groceries and dropping a can of soup, it works well to think the soup stops moving forward when it falls, so that retrieving the can means returning to where it fell. Part of the task of identifying the assumption is identifying a representative situation in which it applies.

Shopping for ideas, students find these and other connections to consider, comparing and contrasting the running drop to experiences such as riding in cars, airplanes, or moving walkways at the airport, and playing basketball, lacrosse, or other sports. Students also relate the running drop to hypothetical but easily imagined situations—"thought experiments"—such as "if you barely tap a baseball in space" or "if you jump out of a moving train."

In summary, the first HTLP objective is for students to engage in this sort of introspection, examining their own minds for various ways of thinking. We expect, and students' essays confirm, that they have resources to do so. However, classroom experience also suggests that the activation of these resources can be tenuous: Students who have started to come up with their own ideas often revert at slight provocation—such as the teacher's hinting at which brainstormed idea is "correct"— to a more familiar epistemological stance, waiting for the teacher to "teach." Consequently, pursuing the epistemological agenda means postponing others. Early in the course, getting students to draw connections is the main goal.

"Stacy's" (pseudonym) first essay on the running drop question, reproduced here verbatim, helps to convey this early agenda and its pursuit in practice:

> If I were running and wanted to drop a quarter on a target, I think the most effective way of doing this is to drop the quarter after I have passed the target. I think the wind resistance will effect the quarter in such a way that, although it may be miniscule, there is still reason to drop the quarter a split second after I pass the target. . . . For example, when a person is driving a car and drops a tissue out the window, the tissue flies through the air behind the car. This is a very extreme situation—the car is traveling at a very high speed in relation to the runner, and the tissue is of very little weight in comparison with a quarter. The high speed of the car will obviously generate a lot more wind resistance than running would, nevertheless this situation leads me to believe that, in running, *some* wind resistance is produced and therefore by dropping the quarter slightly after the target, one accounts for that resistance. Another related example is that if a person with long

> hair runs, her hair flows behind her—it certainly does not jump ahead of her. Likewise with a person's clothing—if a person has a loosely fitted shirt on, the shirt will cling to the front of his body while flowing behind him.
>
> Another theory of when to drop the quarter would be to do so directly over the target. Although I am running with the quarter, and the quarter is moving with me, once I drop the quarter it is no longer moving forward. Therefore, if I drop the quarter directly over the target, it will fall on the target. Gravity will pull the quarter down directly over the target. The quarter is heavy enough and is substantial enough in mass so that it should remain unaffected by the meager wind resistance produced when I am running.
>
> I do not believe that this theory would work in actuality. If a person is standing still over a target, and drops the quarter directly over the target, the quarter will hit the target (notwithstanding that person's aiming abilities). Therefore, it seems obvious that the situation changes if the person holding the quarter is running. When someone is trying to make a "slam-dunk" in basketball, s/he does shoot the ball directly over the hoop. That person is also stopped in mid-air, even if it is only for a split second. The person running and dropping the quarter does not stop, therefore the basketball metaphor is not applicable.

At this moment, Stacy was considering the choice between two answers, neither of which was correct (as she and the class would eventually decide). However, with respect to the course agenda that she become aware of her thinking, this was a strong first essay, especially for Stacy, who had a "terrible experience" in high school physics and entered the class as one of the more intimidated students. Her essay contains nothing explicitly epistemological, in the sense we are using the term; the question asked her to discuss a dropped object, not to discuss knowledge. Still, working from the assumption that her epistemology is involved in her approach to learning, Stacy's essay indicates her activation of productive resources for understanding the relevance of her prior knowledge and the activity of shopping for ideas.

Responding to Stacy's work, David hoped to support these activations. For that reason, he chose not to comment on the correctness of her reasoning and responded instead to endorse what she was doing ("Good comparisons, and very clearly written") as well as to clarify her thinking ("It sounds as though you agree with everything [in the second paragraph counter-argument] but the last idea, that the quarter will not be affected by the wind.").

Physics educators, even those who endorse our epistemological agenda in the abstract, often object to these sorts of responses to student work, on the grounds that it "misleads students" not to correct their misconceptions. As the course progresses, the agenda shifts to include students' understanding of the Newtonian system, more in line with conventional practices.[7] Initially, however, the principal objective is to help lay an epistemological foundation for the study of physics. In that regard, Stacy was making excellent progress. Immediately challenging the particular connections she found in her knowledge and experience may have dissuaded her from seeking those connections, deactivating the productive resources she was beginning to apply. This is not simply a matter of self-confidence; we do not avoid challenging students' thinking only to make them feel comfortable and encouraged (although these may also be important at times). Other student essays on the first assignment are more correct but less connected to everyday thinking. Many make no connections to experience, quoting only from a previous physics course. In these cases, it can be appropriate to challenge their thinking directly, pressing them to shift from trying to remember what they have been told to shopping for more familiar ideas in their everyday knowledge and experience.

Learning to refine everyday thinking

Learning physics requires more than just finding ideas from prior knowledge and experience. Students must also examine those ideas, consider how different ones seem to agree or conflict, and find ways to fit them together. From the start, HTLP asks students to reconcile inconsistencies, the task in part C of essay questions.

Stacy made a good attempt to reconcile her part B counter-argument with her part A reasoning about when to drop the quarter: People may think the quarter no longer moves forward once it is released, she argued, based on their experience in situations like the slam-dunk in basketball. The running drop is different, she claimed, because the person running does not stop.[8]

Many introductory physics students, however, do not work to reconcile inconsistencies they find in their reasoning (diSessa, Elby, & Hammer, in press; Hammer, 1994b; Redish et al., 1998). Interpreting this observation in terms of epistemological resources generates a different set of possibilities for instruction than does interpreting it in terms of developmental limitations, learning styles, or unitary epistemological theories. On a resources-based perspective, students have epistemological resources for understanding the value of spotting and reconciling inconsistencies. Students abide inconsistencies in physics class, because, instead of applying those “reconciliation” resources, they are applying other resources that are useful in other circumstances.

It is easy to see why they would apply other resources. In most problem solving, the objective is to arrive at an answer. Science teachers almost always grade examinations and homework assignments for correctness. Outside of school, questions almost always arise out of the need for an answer—what to have for dinner, which candidate to support in an election, which car to buy. When finding the answer is the objective, reconciling inconsistencies in one's understanding is not usually necessary. For example, one familiar decision-making strategy is to list "pros and cons" and choose the side with more "weight." Once the decision is made, however, the goal is attained, and there is no point to revisiting the reasons on the other side. Having chosen pasta for dinner, it would be dysfunctional to study for flaws in the reasons to order rice. In learning physics, by contrast, the purpose of thinking about questions is not to arrive at answers but to develop a coherent understanding; problems are a means for identifying and reconciling inconsistencies.[9]

In this way, we see difficulties arising from students applying the wrong set of epistemological resources. The instructional task, on this view, is to look for reconciliation resources elsewhere in students' experience. In what contexts, we ask, might students naturally understand the need to reconcile inconsistencies?

The courtroom strategies we mentioned above apply here; contexts more familiar to students might include arguing with parents over curfews and other rules. We have also noted students' expertise with sports and games, which includes resources for understanding the need for consistency. To function, a game must be internally consistent, and if two of its rules disagree in some situation, most players would recognize that one rule or the other should be adjusted to reconcile the disagreement.

More generally, students are likely to have resources for understanding the need to reconcile disagreements among people, and these approaches may help activate those resources for understanding the need to reconcile disagreements among perspectives. In this way, students can see the task not only in terms of finding the right answer but also in terms of being able to respond to counter-arguments: "You've got good reasons for thinking that you have to drop the ball before the target, but how do you respond to the reasons you've heard for dropping it after?"

There may also be relevant resources in the everyday act of "making excuses," especially for errors of mind (e.g. "I'm sorry I'm late, but I got off at the wrong exit. I commute that way, and out of habit I drove to work!"). Just as an everyday excuse can be used to account for the tardiness of an otherwise responsible individual, an epistemological "excuse" can be used to account for the failure of an otherwise reasonable idea.

Another strategy for helping students activate productive resources is to consider a task with familiar content, such as arithmetic:

> Suppose you're teaching second grade math, and one of your students writes '2 x 7 = 77.' What could he be thinking, and why would he be wrong?[10]

This also shifts the context to one of teaching, which may again help students take a constructive approach to discrepant thinking.

Students in HTLP discuss the epistemology of various situations, as reference points for considering how to use problem solving to learn physics. Teaching HTLP, David listens and reads, still not primarily for correctness, but for signs of students' attempting to coordinate and reconcile multiple perspectives.

Stacy's first-draft response to the running drop problem showed that she was trying to reconcile inconsistencies. Later, after informal experimentation, class discussions, and reading other students' essays, Stacy changed her mind to conclude that one must drop the quarter before the target. In her revised essay, she worked to reconcile her earlier thinking, focusing in particular on the connection she had made to throwing a piece of tissue paper out of a car window:

> There are many everyday situations that seem to prove . . . that the quarter should be dropped after instead of before the runner passes the target. For example, the situation of a tissue being thrown out of a car window may give someone this idea. Obviously, that tissue (if the car is moving at an ample speed) will fly backward. Therefore, wouldn't the quarter fly backward also, even minimally? The answer is no [because] there is a rather large amount of wind resistance, blowing the tissue backward, that is generated by the car. A tissue is of very little weight and will be affected easily by the wind. Inertia effects all objects, but can be counterbalanced by other forces such as gravity and wind resistance. In the case of the quarter being dropped by the runner, inertia is a greater force than wind resistance. In the case of the tissue being thrown out of the window, the opposite is true.

In other words, Stacy argued, the idea that the quarter would fly backwards would be correct for a tissue thrown from a car, but that is because the tissue is "affected easily by the wind." By contrast, the quarter is less affected by the wind and can continue to move forward, its inertia overcoming the force of the wind. Although not yet working within a Newtonian framework, Stacy was reconciling her different experiences to a local, internal coherence.

For contrast, consider Doug's response to a subsequent version of the same question, posed after the class reached a consensus about the original question. The new questions asked,

> After you let go of the quarter, does it keep moving forward at the same speed that you're moving forward, or faster, or slower, supposing you keep running at a constant pace in a straight line?

Doug answered that the quarter would continue to move forward at the same speed:

> I think this because of my prior knowledge of inertia and that an object in motion will remain in motion until it is acted upon by an external force.

Quoting prior knowledge from a previous physics course, he had what physicists consider the correct answer. He was further able in part B to find an alternative line of reasoning and to express it clearly:

> Another answer to this question that one might be tempted to think is that once released the quarter will travel faster. One might reason that this is true because in addition to the speed created by your running there is the speed created by gravity. This means that the energy you invest in the quarter is amplified by the energy gravity creates. The energy of the horizontal and vertical movements combine to produce a faster speed. If this were true, I think that one would observe the quarter touch the ground at a point ahead of you.

His response to part C ("what's wrong with the reasoning in part B?"), however, suggested that he did not yet understand the task:

> This answer is flawed in that when conducting the experiment I can observe that the quarter touches the ground next to me. I also think the reasoning behind the combination of "energies" is simply physically impossible, although I cannot provide evidence for this.

In other words, the "flaw" in the alternative line of reasoning is simply that it gives an incorrect result. Doug, like many HTLP students early in the course, seemed not to understand the notion of reconciling an inconsistency; he simply contradicted the reasoning he did not accept.[11] With greater epistemological sophistication, Doug might have spent more time and effort trying to find the flaw in his part B argument. Unfortunately, Doug showed little improvement over the course.

Understanding the goal of principled consistency

Ultimately, success in learning physics requires students to embrace a principled theoretical framework—here Newton's Laws of Motion. Although traditional courses presume that students understand and value principled consistency, evidence shows most do not, at least not in the context of introductory physics. We assume students have resources for understanding principled consistency, and we try to help them find and apply those resources to their learning. HTLP approaches this in terms of "foothold ideas," precision, and commitment.

Trying to reconcile inconsistencies, students sometimes experience difficulty in deciding which ideas to modify and which to maintain. Students may hesitate to choose an idea to *hold* fixed when they are not sure it is correct, partly because they are applying resources for understanding knowledge as *inherently* fixed, "simple" (Schommer, 1994), and evident in the world through observation (Carey & Smith, 1993; Linn & Songer, 1993). Such resources are productive in many contexts, but in reasoning about new questions students often need to make suppositions and explore their implications. In what everyday contexts do they activate resources for understanding ideas as conjectures?

One example is arranging furniture. It is a familiar strategy to put one piece somewhere and then consider the implications of that placement for others ("Try putting the couch under the window. OK, then the only place for the loveseat is by the door. . . ."). Similar approaches can apply to fitting luggage in a trunk ("Maybe if we put the biggest one in first?"), writing a story ("If I have Eloise die in May she can't be the one who saves Simon in June."), and so on. These are all activities of design; many students invoke similar resources in contexts of building gadgets or writing computer programs to accomplish some task. Educators (Harel & Papert, 1991; Hmelo et al., 2000; Penner et al., 1998) have advocated design activities because, in our language, these help tap productive epistemological and metacognitive resources. For our purposes, familiar contexts of design may serve as epistemological anchors for analogies to help activate these resources.

David defines for students the notion of a "foothold idea" as "something you choose to accept as true, at least for a moment, and use as a basis for further thinking." Foothold ideas contrast with hidden assumptions not only with respect to awareness and intentionality but also with respect to precision and commitment. First, to be useful, a foothold idea must be sufficiently precise; vague footholds have ambiguous implications. Second, because a foothold idea is a deliberate assumption, students should have a sense of the level of their commitment to it, whether it is a tentative supposition or an idea they expect must be true.

Again, students display relevant everyday expertise. The need for precision is clear when designing or modifying rules of a game or rules of behavior. For example, the New Year's resolution to "exercise more" serves as a poor foothold—what constitutes "more"? A more precise resolution does more to constrain later interpretation: "I will run 12 miles every week."

The exercise example invites discussion of commitment and modifiability. If, for example, after two weeks of adhering to the resolution a conflict arises with health or schedule, the person may decide to modify the rule, perhaps to run 10 miles per week or to allow for certain exceptions. Other possibly familiar contexts include societal laws. These again must be sufficiently precise to constrain interpretation in contentious situations. They also come with varying levels of commitment: Our judicial system holds a higher commitment to the Constitution than to new legislation.

These discussions also address the role of experiments in science and science learning. A good experiment can provide an firm foothold idea, a basis for . For students, experts can play a similar role, providing information as footholds for constructing their understanding. To view experimental results or expert pronouncements as footholds, meanwhile, is to see them as possibly open to adjustment, such as if they conflict with other high commitment ideas.

The notion of varying levels of commitment is particularly important and difficult. Students often expect ideas in science to be unambiguously true or false; some may also think of scientific ideas as arbitrary, "just another perspective." Activating resources for understanding different levels of commitment allows a more refined stance toward truth in science. A useful and amusing metaphor is the notion of "dating" an idea, making a temporary commitment "just for lunch" to see how things work out. As it would be socially paralyzing to refuse to spend time with anyone for fear that "he isn't Mr. Right," it is cognitively paralyzing to insist on knowing whether a particular idea is correct before trying to apply it. The metaphor applies also to high commitment. As one idea proves to be consistent with others, and as apparent conflicts can be reconciled, we may have reason to "marry" it.[12] In this way, we guide students toward understanding the "laws of physics" as extremely high commitment footholds, with the commitment based on a history of success in explaining, predicting, and reconciling knowledge and experience.

For example, students find it extremely difficult to decide based on experimentation alone whether the quarter in the running drop keeps pace with the runner. Even the fact that the quarter continues to move forward can be problematic to observe.[13] Paula, for example, had originally concluded "that you should drop the quarter directly above the target," "based on actually trying to do it." Class discussion and further experimentation led her to revise this view, first to concede that the "quarter does indeed move forward after being dropped. . . but *just a little*," and then to the view that the quarter keeps pace with the runner:

> I envisioned the quarter travelling only a few inches forward, almost to the point that you wouldn't notice it unless you were looking for it. We were, of course, looking for it, and after observing a trial I was very surprised. After David dropped his keys, they traveled forward a distance judged to be about three feet or more— it was certainly noticeable. . . . Thinking about it, I realized that the object dropped <u>continues to travel at the same speed</u> as the person who had carried it, until it lands on the ground. . . . Just as a quarter at rest will not START moving on its own (until some source of energy is applied to it), a quarter in motion will not STOP moving on its own (until some source of energy is applied to it). [emphasis in original]

HTLP was not Paula's first course in physics. She had, in an earlier essay, described a "vague memory. . . of high school physics, that involved the property of objects in motion tending to stay in motion." Revising her thinking about the running drop, she examined her earlier reasoning and found a way to reconcile it with the idea that an object continues to move at the same speed. Her essay was unusually articulate and perceptive, a striking example of a student's shopping for ideas, identifying hidden assumptions, and working to reconcile inconsistencies:[14]

> Another response that someone might have to this question is that the quarter will move forward, but slower than the person running. This could make a lot of sense if your viewpoint is as follows. It would seem that the world is at a natural state of rest, and that when things move, they come back to rest again. What goes up comes down, what speeds up slows down, people get tired, fires go out, and rain eventually stops

> falling. It seems like there may be a universal force that brings everything back to this inherent state of rest. It would make sense, then, that when the force propelling the coin forward "lets go" of the coin (both literally and in a more abstract sense), the natural tendency to come to rest would come into play and the forward velocity of the quarter would be reduced.
>
> The reason that this argument does not work is that the "universal force" that brings objects back to rest is not universal at all; it is really many, many different and varied forces that come into play in specific ways. Fires go out when, among other reasons, fuel is depleted. People tire because the energy they get from food and rest is finite and needs to be replenished regularly. Objects fall to the earth because of gravity. And objects travelling forward do tend to slow down, but for reasons that again are very specific and not mystical at all. Motion on the earth's surface or the surface of other objects can be hindered because of friction. Sometimes the force of friction is very great, such as two pieces of sandpaper rubbing together, or it could be very weak, such as wet snow sliding off the hood of a car. . . . [The air resistance against the quarter] is the one element of the "universal force" that I invented that actually applies to the forward motion of the quarter—in this case, we can ignore that force because it really isn't forceful at all.

A standard interpretation of Paula's success in HTLP[15] would cite her previous exposure to the material as giving her an advantage. We suggest the plausibility of an alternative interpretation, that Paula was applying a different set of epistemological resources for learning, resources that, in her case, seemed to be especially well-developed. The key point here is that, rather than starting from scratch when introducing students to the epistemological belief that understanding physics requires a commitment to principled consistency, we try to locate and build on "principled consistency" resources students already possess but apply in other contexts. By contrast, a unitary view of epistemologies would indicate the need of first eliciting and dislodging the (mis)belief that physics knowledge consists of weakly-connected pieces.

We have not argued here, or presumed to have given evidence, that the methods of HTLP are generally effective. To be sure, for some students it is clear they were not; as we noted, Doug showed little improvement. Our claim is that the instructional strategies, homework assignments, and assessment criteria in HTLP reflect the theoretical position that Doug, Stacy, Paula and other students already have productive resources for understanding how to learn physics. Thus David designed the course to help students activate apply those resources, refine and extend them to new uses, and ultimately form them into new commitments and habits of mind. Doug's problem, in this view, was not that he lacked those resources, but that HTLP failed to help him activate them, for any of a variety of reasons. Stacy and Paula, by contrast, each showed substantial progress.

We note in closing this section that David began developing HTLP in 1994, well before we had begun to think about epistemological resources as a research agenda. Of course, a similar body of education research helped shape his thinking then as has informed our research now (see references in Hammer & Elby, 2002; see also Hammer, 1997), and having articulated this perspective has led to new ideas for his teaching. Still, the history of HTLP illustrates what we noted above, that in formulating an account of epistemological resources we draw heavily on our more tacit insights as teachers.

STRATEGIES FOR MORE TRADITIONAL SETTINGS

HTLP's unusual freedom from outside constraints allows an extended, specific focus on epistemology. In most circumstances, however, teachers must coordinate epistemological and other inquiry-oriented objectives with traditional content-oriented ones (Hammer, 1997). In this section, we describe curricular elements and strategies that can be implemented in regular science courses.

We draw in particular on two high-school courses Andy taught, at public schools in California and in Virginia. In 1997-1998, Andy taught in the regular

Physics track at the school in northern California. The students, mostly juniors and seniors, were heterogeneous in terms of ability and motivation.[16] The school in Virginia is a math/science magnet, with highly selected students. In 1998-1999, Andy taught Physics 1, which is required of all juniors and would be considered honors-level at most high schools. In both classes, the students were mostly White or Asian, from middle class backgrounds, and roughly evenly split by gender.

At the California school, Andy had substantial control over the curriculum, constrained only by the Department Chair's general expectations. The course proceeded at a relatively slow pace as compared to standard physics courses, covering large segments of mechanics, waves, and optics in detail, but skipping most of electromagnetism. In Virginia, the coverage was tightly constrained, with several sections taught by different instructors assessed by common semester-end examinations. The course covered mechanics, electromagnetism, and waves in sufficient detail to prepare students for the SAT II in Physics, with some teachers also touching upon thermodynamics and/or modern physics.

Elby (2001) describes these courses in more detail. Here, we focus on how some adjustments to familiar methods reflect a resources perspective on student epistemologies. Mining again for insights embedded in instructional practice, we describe instructional elements of Andy's work in these two settings. His epistemological objectives resembled David's in HTLP, that students come to understand learning physics as a matter of refining everyday thinking toward precision and consistency. Andy, however, needed to weave these objectives into the canonical agenda. We illustrate this weaving with examples of (1) laboratory activities, (2) explicitly epistemological questions, and (3) adaptive curriculum strategies.

Laboratory activities

We present two examples of laboratory activities, on Newton's 2nd and 3rd laws respectively.

Newton's 2^{nd} law lab

The first force lab, a version of which students used in both California and Virginia, begins by eliciting and confronting a common student difficulty, in the style of "Tutorials" (McDermott & Shaffer, 1998):

1. A car cruises steadily down the highway at 60 mph. Wind resistance and friction oppose the car's motion. Those backwards forces have a combined strength of 5000 Newtons. The car's engine causes a forward force to be exerted on the car. Intuitively, is this forward force less than 5000 Newtons, equal to 5000 Newtons, or greater than 5000 Newtons? Explain.

2. In this question, we'll see if Newton's 2nd law agrees with your intuitive guess.

(a) When the car cruises at constant speed 60 mph, what is its acceleration, a? Explain your answer briefly.

(b) Therefore, according to $F_{net} = ma$, when the car moves at constant velocity, what net force does it feel?

(c) So, is the forward force greater than, less than, or equal to the 500-newton backward force? Does this agree with your intuitive answer to question 1?

The assignment then asks students to reflect explicitly on epistemology.

3. Most people have—or can at least sympathize with—the intuition that the forward force must "beat" the backward force, or else the car wouldn't move. But as we just saw, when the car cruises at steady velocity, Newton's 2^{nd} law says that the forward force merely *equals* the backward force; $F_{\text{net}} = 0$. Which of the following choices best expresses your sense about what's going on here?

(a) $F_{net} = ma$ doesn't always apply, especially when there's *no* acceleration.

(b) $F_{net} = ma$ applies here. Although common sense usually agrees with physics formulas, $F_{net} = ma$ is kind of an exception.
(c) $F_{net} = ma$ applies here, and disagrees with common sense. But we shouldn't *expect* formulas to agree with common sense.
(d) $F_{net} = ma$ applies here, and appears to disagree with common sense. But there's probably a way to reconcile that equation with intuitive thinking, though we haven't yet seen how.
(e) $F_{net} = ma$ applies here. It agrees with common sense in some respects but not in other respects.

Explain your view in a few sentences.

It is interesting to note that the academically heterogeneous students at the California school were divided fairly evenly across answers (b), (c), and (d), while the magnet program students in Virginia mostly chose (d) or (e). That is, the academically selected students were more inclined to expect coherence between the formula and common sense.

On a unitary view of epistemologies, we might attribute this difference to characteristics of the students. On a resources view, we expect to be able to help students activate productive resources, in this case for expecting coherence and reconciling inconsistencies between formal laws and common sense. The remainder of the lab was designed to help them tap those resources, in addition to helping them understand Newton's 2^{nd} law.

Students began by pulling a cart across the carpet (which created appreciable friction) with a rubber band.[17] They were asked to focus on the following issue:

4. Is there a difference between how hard you must pull to *get* the cart moving, as compared to how hard you must pull to *keep* the cart moving? You can answer this question by "feeling" how hard you're pulling, and by observing how far the rubber band is stretched.

Students could see and feel that more force was needed to initiate than to maintain the motion. In follow-up questions, students related their experimental observations to Newton's 2nd law:

5. Let's relate these conclusions to Newton's 2nd law.

(a) While you *get* the cart moving (i.e., while it speeds up from rest), does the cart have an acceleration? So, does the forward force *beat* the backward force or merely *equal* the backward force? Explain.
(b) While you *keep* the cart moving (at steady speed), does the cart have an acceleration? So, does the forward force *beat* the backward force or merely *equal* the backward force? Explain.
(c) Using your part (a) and (b) answers, explain why more force was needed to *get* the cart moving than was needed to *keep* the cart moving.

Question 6 then asked students about the force needed to get the cart moving vs. to keep it moving in the absence of friction. Finally, question 7 asked students to summarize for themselves the main conceptual point of the lab:

7. OK, here's the punch line. Most people have the intuition that, if an object is moving forward, there must be a (net) forward force. Explain in what sense that intuition is helpful and correct, and in what sense that intuition might seem misleading.

Most students responded that the "motion requires force" intuition applies to getting an object moving but not to keeping it moving.

In this way, the lab guided students to identify a conflict between Newton's 2nd Law and their intuition that motion requires force. Many reformed courses do the same but treat the intuition as a misconception to reject, often with the tacit if unintended message that physics is "counter-intuitive." Here, the lab prompted students to reconcile the conflict by adjusting their intuition, with the careful message that intuition can be helpful.

The Newton's 2nd law lab reflected Andy's attention to epistemologies, but it could have been designed by someone with a unitary perspective. Question 3 could be seen as eliciting students' epistemological theories; questions 4 through 6 as confronting less sophisticated views; and question 7 as providing a more expert alternative. In the ensuing class discussion, Andy's resources perspective became apparent. Among other things, he introduced an analogy between learning and cooking. When a culinary recipe doesn't work, the cook can either (i) throw out the original recipe and try a new one, or (ii) refine the original recipe, perhaps repeatedly, until the result tastes good. Similarly, when an intuition doesn't work, a student can either abandon that intuition or try to refine it until the result "tastes good" in the sense of agreeing with observations and with physical laws. Andy's use of this analogy presumed that students have resources for viewing knowledge as something that can be modified, like a recipe.

In 1997, while Andy held an explicit resource-based view of students' *conceptual* knowledge (diSessa, 1993), he was only beginning to articulate a corresponding view of epistemologies. Like other teachers, his expectation of productive epistemological resources was mostly tacit. As he developed an explicit account, the view had new influence on his teaching. In 1998 he designed the following lab that specifically applies an expectation of productive resources for understanding intuition as raw material and learning as its refinement (e.g. *Knowledge as fabricated stuff*, learning as knowledge *Formation* rather than *Accumulation*, and so on).

Newton's 3rd law lab.

Once again, the beginning resembles a Tutorial or a RealTime physics lab (Sokoloff, Laws, & Thornton, 1998):

1. A truck rams into a parked car. The truck is twice as massive.

(a) Intuitively, which is larger during the collision: the force exerted by the truck on the car, or the force exerted by the car on the truck?

(b) If you guessed that Newton's 3rd law does *not* apply to this collision, briefly explain what makes this situation different from when Newton's 3rd law *does* apply.

2. (*Experiment*) To simulate this scenario, make the "truck" (a cart with extra weight) crash into the "car" (a regular cart). The truck and car both have force sensors attached. Do whatever experiments you want, to see when Newton's 3rd law applies. Write your results here, continuing on back if needed.

On question 1, most students wrote that the car must feel a larger force, since it reacts more. Therefore, the experimental confirmation of the 3rd law in question 2 might reinforce students' view that intuitions are not to be trusted in physics class. The follow-up questions attempt to activate resources of refinement:

3. Most people have the intuition that the truck pushes harder on the car than vice versa, because the car "reacts" more strongly during the collision. But Newton's 3rd law applies. So, should we toss that intuition into the trash and just accept that Newton's 3rd law violates common sense? Well, before taking that step, let's clarify the "reaction" intuition to see if we can reconcile it with Newton's 3rd law.

(a) During the collision, suppose the truck loses 5 m/s of speed. Keeping in mind that the car is half as heavy as the truck, how much speed does the car gain during the collision? Visualize the situation, and trust your instincts.

Most students answer, correctly, that the car gains twice as much speed as the truck loses. This intuitive idea agrees with Newton's 3rd law, as students discover by working through parts (b) through (e):

(b) Does your part (a) answer agree with Newton's 3rd law? To find out, we'll need to do a few calculations. During the collision, the truck and car stay in contact for 0.25 seconds. Calculate the car's acceleration and the truck's acceleration. Which one is bigger, and by what ratio? (Twice as much? Three times as much?)

(c) Let's say the truck has mass 1000 kg and the car has mass 500 kg. Assuming negligible friction with the road during the collision, the forces exerted by the car and truck on each other are the net forces experienced by each vehicle. Using the accelerations from part (b), calculate $F_{\text{truck on car}}$ and $F_{\text{car on truck}}$.

(d) Your part (c) answers stem from your guess about how the car's change in velocity compares to the truck's change in velocity—a guess that reflects your "reaction" intuition. Does this intuition agree with Newton's 3rd law?

(e) We already knew that Newton's 3rd law is true. So what was the point of this whole question?

Most students correctly reach the conclusion that, if the car speeds up by twice as much as the truck slows down, then both vehicles must have felt the same *force*. The subsequent questions emphasize the epistemological importance of this conclusion:

4. In question 3, the intuition that the car reacts more than the truck during the collision leads to a conclusion ("the car's velocity changes twice as much as the truck's") that *agrees* with Newton's 3rd law. But in question 1, that same intuition leads many people to think that the truck exerts a larger force on the car than vice versa, a conclusion that *disagrees* with the 3rd law. What's going on here? How can the *same* intuition ("car reacts twice as much as truck") lead to two *different* conclusions, one of which is right and one of which is wrong?

5. Here's how some people reconcile the paradox from question 4:

"My intuition says that the car reacts more strongly than the truck reacts during the collision. But by thinking through my intuitions carefully in question 3, I found that my 'reaction' intuition is actually an intuition about ____________________, not force."

Fill in the blank.

Questions 4 and 5 invite students to view their conflicting intuitions as two versions of the same idea, that the car reacts more strongly than the truck during the collision. By finding that one of those versions is correct and helpful for understanding Newton's 3rd law, students experience the sense in which the refinement of everyday thinking is part of learning physics.

Class discussion: Refinement of raw intuition

The next day, Andy led a class discussion designed to underscore this point. He introduced the distinction between a vague, *raw intuition*, such as "the car *reacts* twice as much during the collision," and a more precise, *refined intuition*, such as "the car feels twice as large a *force* during the collision" or "the car has twice as much *acceleration* during the collision."

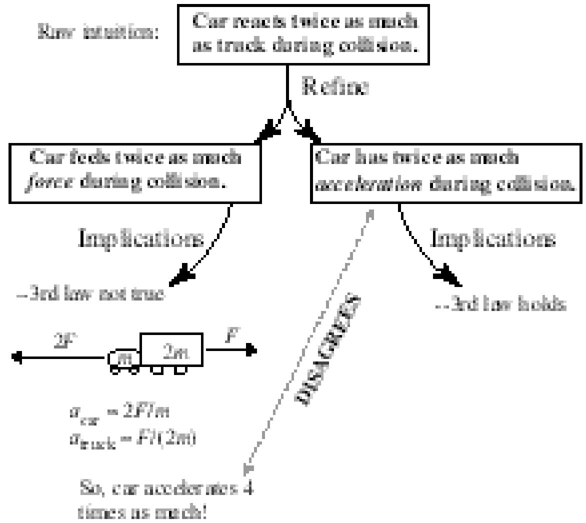


FIGURE 2: Schematic of whiteboard at the end of the "refinement" lesson. Students traced the consequences of refining the *raw intuition* "the car reacts twice as much as the truck" in two different ways.

In a whole-class conversation punctuated by small-group discussions and problem-solving interludes, students decided that they possessed the raw "reaction" intuition long before entering physics class. Andy confessed that lab question 1 is designed to push students to refine that intuition in terms of forces, while question 3 pushes students to refine it in terms of changes in velocity (or acceleration). Students then traced the implications of those two refinements more fully than they did during the lab itself. The refinement in terms of acceleration not only agrees with, but also helps to explain Newton's 3rd law: The car reacts more than the truck not because it feels a greater force, but because it is less massive and therefore "reacts" more to the same force. By contrast, the refinement in terms of force disagrees with the 3rd law, and also leads to the suspicious conclusion that the car accelerates *four* times as much as the truck during the conclusion. Figure 2 depicts the whiteboard at the end of this discussion.

We now discuss more fully the connection between Andy's force labs and our resources view of epistemology. Students have resources for understanding learning in terms of receiving and retaining information. These resources are productive in many situations, e.g., when you ask at what time the next train arrives. Similarly, students have resources for understanding the correctness of information, and for seeing learning as involving the replacement of incorrect ideas. Again, this is often productive: "I thought that trains come every 10 minutes, but I'm wrong, they come every 20." However, with these epistemological resources active in a physics class, students would tend to see some of their common-sense ideas as mistakes that must be corrected: "I thought the car would need an overall forward force to move, but according to Newton's 2nd law I was wrong."

Fortunately, students also have resources for understanding the refinement of prior knowledge, for reconciling inconsistencies in their thinking: "I thought that trains come every 10 minutes, and that's partly right; they come that often during rush hour, while at other times, only half as many trains are running, so they come every 20 minutes." With "refinement" resources active, students would be inclined to adjust their intuitive ideas instead of discarding them: "I thought the car would need an overall forward force to move, and that's partly right; a forward force is needed to initiate the motion but not to maintain it." The force labs and lessons aim to help students activate these resources, to become aware of their activation, and to see their value for learning new concepts.

Again, these lessons presume a manifold as opposed to unitary framework for understanding intuitive epistemologies. Specifically, we assume that students walk into the classroom already capable of reconciling their intuitions with physical laws *and of understanding that that is what they are doing*—activities they could not do without having refinement-related resources already in place.[18]

Epistemological homework questions

Like other reform-minded teachers, Andy included qualitative, "conceptual" question on homework and examinations, asked for reasoning and explanations rather than just answers, and avoided questions that could be answered based on rote application of equations. In addition, he peppered assignments with questions focused explicitly on epistemology. (To encourage honesty as opposed to "telling the teacher what he wants to hear," he based grading on the completeness, not the content, of their responses.) Examples include the following:

> Think about the material you learned for last week's quiz [about kinematics graphs].
> (a) What role did memorization play in your learning of the material?
> (b) What makes the material "hard"?
> (c) What advice about how to study would you give to a student taking this course next year?
> [*In California, asked in October and again in January*]

> On last week's circular motion lab, there were experiments, conceptual questions about those experiments, and "textbook-like" summaries. In each case, the summary came *after* you attempted to answer some questions about the material covered in the summary. But on other labs, I've put the summaries *before* the related questions.
> **(a)** When it comes to helping you learn the material, what are the advantages of putting the textbook-like summaries *before* the conceptual questions about that same material? Please go into as much detail as possible.
> **(b)** When it comes to helping you learn the material, what are the advantages of putting the textbook-like summaries *after* the conceptual questions about that same material? Please go into as much detail as possible.
> [*California*]

> In lab last week, most people seemed surprised to find an apparent contradiction between common sense and Newton's 2nd law (F_{net} =

> *ma*), for a car cruising at constant velocity. But the night before the lab, you read a textbook section about Newton's 1st and 2nd laws. Why didn't you notice the apparent contradiction while doing the reading?
>
> I'm not "yelling" at you or blaming you; I know you're careful, conscientious readers. That's why it's *interesting* to think about why the apparent contradiction went unnoticed. What could you and/or the textbook have done differently to help you discover—and possibly resolve—the apparent contradiction?
>
> [*Virginia*]

Having students reflect on their learning is hardly a new idea. If the above reflection questions differ from those used in other curricula, it is in their narrowness. The questions ask students to focus on specific learning issues: the value of memorization, the difference between "taking in" knowledge before vs. after trying to construct one's own understanding, the failure of standard textbook reading to help students uncover conflicts with common sense. By reflecting upon very specific behaviors, both productive and unproductive, students can begin to stabilize the underlying epistemological resources into consciously held strategies and beliefs about learning.

Adaptive curriculum strategies

So far in this section, we have emphasized curricular elements Andy developed to address students' epistemologies. He also used other, more familiar strategies. Here, we briefly note two of them, showing how they relate to the resources perspective.

Reduced use of (traditional) textbook

In both California and Virginia, the textbook covered a huge range of topics, devoting little space to each one. Within a given chapter, the textbooks typically begin by introducing formal definitions and equations, followed by a few examples and real-life applications. By contrast, Andy was trying to teach students that learning physics often involves *starting* with everyday knowledge and experience, and building from there to formal definitions and equations. A major goal was for students to unearth and examine their own intuitive ideas, refining them when needed, an activity the textbook did not address or support. Due to this epistemological tension between the book and the instructor's goals, Andy assigned readings only once or twice all year.

The resources framework thus presents a particular critique of traditional textbooks. Students who employ an epistemologically sophisticated approach to learning physics use a textbook very differently from the way average students do (Hammer, 1994). The sophisticated students often stop to reflect upon passages they just read, work through examples, invoke their personal experiences, and use other active-learning techniques. For most students, however, conventional textbooks are likely to cue "transmissionist" resources (*Knowledge as propagated stuff*, *Accumulation*, and so on).

Fluid lesson plans

Although his courses lacked the freedom of HTLP, Andy had some flexibility regarding the curriculum, especially in California. His decisions in responding to students were shaped in part by his objectives of activating productive resources and deactivating counter-productive resources students might be inclined to apply to a physics course.

For instance, during a friction lesson in California, the class did an experiment in which a heavy and light book with the same cover are “kicked” across the floor with the same initial speed. The two books slid the same distance. The ensuing class discussion was intended to help students make sense of this result both intuitively and mathematically. But "Jim" wondered aloud why, when an equally-fast car and truck slam their brakes, the truck takes longer to stop. Andy, seeing a "teachable moment," chose to pursue this question, highlighting the fact that reconciling everyday experience and intuitions with each other and with physics principles is an essential part of learning physics. To reinforce this point, he replaced the planned homework assignment with the student's car question, followed up by class discussion the next day.

Taking advantage of teachable moments is standard practice; teachers often use a student's curiosity or disequilibration concerning a particular issue to focus on a general concept. The Jim example illustrates how a theoretical perspective can prepare an instructor to notice particular kinds of teachable moments, in this case an epistemological one: Andy recognized Jim's activation of productive resources. As important as it is to design instruction to help students activate productive resources, it is just as important for a teacher to respond positively when students do this for themselves.

This point deserves further comment. In this article, we have emphasized curriculum design. At least as important, with respect to fostering epistemological development, is the teacher's role in diagnosing the strengths and weaknesses in students' knowledge, reasoning, and participation. The resources perspective anticipates variation and idiosyncrasy within and between students, and it may help teachers — we believe it helps us — recognize and respond to the particularities they encounter in their classes. When searching for pockets of everyday epistemological expertise relevant to learning physics, teachers must anticipate that these pockets and their activation will vary from student to student and class to class. Teachers constrained for coverage face especially big challenges in making time for this flexibility. In our view, teachers are more inclined to take on that challenge when their framework for viewing students' epistemologies gives them reasons to believe that pockets of everyday epistemological expertise exist and can be redirected toward learning physics.

In closing this section, we briefly point to evidence that, with respect to learning physics in a classroom context, students ended the courses with more sophisticated epistemologies than they started with. Pre-post results from the Maryland Physics Expectations Survey (Redish et al., 1998) and the Epistemological Beliefs Assessment for Physical Science (White, Elby, Frederiksen, & Schwarz, 1999) indicate that students developed more sophisticated epistemological stances regarding the nature of physics knowledge, and regarding the constructive nature of learning. Further evidence suggests that these gains did not come at the expense of conceptual understanding.[19] See Elby (2001) for details.

SUMMARY

Just as research on conceptual knowledge has been dominated by views of alternative frameworks and misconceptions, research on epistemologies has depicted students as holding context-independent, counter-productive epistemological theories. Following work in intuitive physics to describe students' conceptual resources, we have begun a program of research to describe epistemological resources.[20]

Our purpose in this article has been to discuss the instructional significance of this shift to a resources-based view: Teachers who ascribe epistemological beliefs to their students will incline toward instructional strategies that differ from those of teachers who ascribe context-sensitive epistemological resources. We have not, however, presented this as a matter of theoretical progress leading to better instruction. In fact, part of our argument in support of a resources perspective is a contention that such a view is inherent in extant instructional practice, and that research on epistemologies has yet to reflect the depth of this mostly tacit knowledge by teachers and curriculum developers. Making this knowledge explicit will benefit research on epistemologies, which may, in turn, prompt more deliberate consideration of student resources in instruction. In describing aspects of our courses, we have tried to illustrate some of this conversation.

We would also like to think that this article could serve as an example of beneficial interplay between the inquiry of teaching and research on learning (Hammer & Schifter, 2001). On a conventional understanding of the relationship, researchers should provide teachers insights into the nature of student knowledge and reasoning, and teachers should implement those insights into their curricula and classroom practices. But our experience in this work has been largely the reverse: In developing a resources perspective on student epistemologies, we are drawing extensively on our experiences as teachers.

That should not be surprising, since like others who play both roles we spend far more time interacting with students as teachers than we do as researchers. Of course, it is generally the case that teachers have more opportunities to explore student reasoning than do researchers. In the area of epistemological resources as in others, we believe further progress will come from fluid conversation between research and instruction.

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[2] Note that we are not claiming knowledge arises spontaneously! We are claiming that this is an element of intuitive epistemology, a resource children may invoke to understand how some of their ideas come to be.

[3] Metacognition may well take place independent of epistemology. In principle, that student might not be able to answer the teacher's question. Or, more familiar, a bicyclist may develop the habit of checking over his shoulder for traffic before making a turn, activating the metacognitive resource without any epistemology involved. For now, however, we defer consideration of the dynamics between epistemological and metacognitive resources.

[4] diSessa's (1993) account affords a fine-grained interpretation: The situation of the spring activates a p-prim, *Springiness*, and the analogy carries that activation back to the book on the table. This cues other primitives, including *Balancing* by which students see a balance between the weight of the book (a downward force) and an upward force by the table. Brown (1993) discussed this role of analogies as "refocusing core intuitions." Here the essential point is that there are such core intuitions to be refocused. That notion in itself is valuable in ways that are not sensitive to the finer-grained details of the underlying conceptual resources. This motivated Minstrell (1992) to coin the term "facets" as a general

reference to students' conceptual resources, without the specific ontological commitments of diSessa's p-prims.

[5] Newton's Third Law states that if there is a force by object A on object B, there is an equal and opposite force by object B on object A.

[6] “The whole of science is nothing more than a refinement of everyday thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of concepts from his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking.” (Einstein, 1936).

[7] It is not our purpose in this article to establish the effectiveness of these methods at teaching students Newtonian mechanics. However, because some readers will be interested to have information for comparison, we have used the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992), a standard measure within the physics education community, as a very rough indication. Stacy's post-instructional score was 83%; class averages for HTLP have ranged from 73 to 78%. These scores are well above typical post-instructional scores in conventional courses (Halloun & Hestenes, 1985) and are within the range of scores achieved by innovative courses more directly concerned with developing Newtonian understanding. (David has not used the FCI as a pre-test, however, out of concern that it could work against the epistemological agenda, at the initial stage of the course. There is no reason to expect, however, that HTLP students' pretest scores would be unusually high. We provide more thorough standardized assessment for Andy’s courses later in the article.)

[8] Her argument in part C does not quite reconcile the difference of viewpoints. From the rest of her argument, it is clear that she agreed with part B that the quarter does not move forward once it is released. One way she might have reconciled the difference would be to say that part A assumes the force backward by the wind on the quarter just before release will affect the quarter after release, whereas part B assumes the prior condition had no effect. She might then explain part B's reasoning as effective for the slam-dunk, because the ball is not moving just prior to release, since the shooter stops "midair... for a

split-second." Of course, little of this agrees with Newtonian mechanics; what is more important at this stage is the internal consistency of an argument.

[9] At no point do we suggest that "there is no one right answer" or that finding the right answer is of no consequence. To the contrary, in physics there very often is "one right answer." For example, the right answer to the original question of the running drop is that the quarter must be released before the target. The answer to a question in a physics course, however, is generally significant only insofar as it aids the construction of a coherent understanding.

[10] He is "right" in that 2 x 7 means "two 7's." It is a notational convention that "77" means something else. Had the question been "2 x  = ?" then "" would be perfectly acceptable.

[11] There are several things Doug might have said in an attempt to reconcile the conflict. One is that the falling quarter does indeed move faster, as the reasoning suggests, but it also travels a longer distance, moving both vertically and horizontally. Thus it is not a contradiction to believe both that the quarter travels faster, gaining energy from its fall, and that the quarter's horizontal speed is unchanged.

Doug had a difficult time throughout the course learning to reconcile different ways of thinking. Although he began the course "ahead" of Stacy in the correctness of his knowledge, he did not make as much progress as she did, either epistemologically or conceptually. (His post-instructional score on the FCI was 70%.)

[12] Of course, the metaphor is not perfect: One can "marry" many ideas, as long as they fit together.

[13] Students sometimes try is to record the event on videotape. Playing it back frame-by-frame allows them to examine carefully whether the quarter keeps up with the runner as it falls. Still, it is often possible to reconcile videotape data to agree with high commitment footholds. On one occasion, for example, the videotape showed the quarter pulling ahead of the runner, a result that conflicted with the students' sense of mechanism. Holding that sense fixed as a foothold, they looked for a way to account for what they saw, deciding that the

quarter's pulling ahead was an appearance due to the shift in the camera's angle as the runner passed.

[14] It is so good an example that it may be important to note that it was genuinely her own work! Paula's "universal force" argument was entirely her construction, not an idea developed in class.

[15] The evidence of "success" is primarily from essays such as this. In addition, her post-instructional FCI score was 80%.

[16] There were two options for physics at this school, "AP Physics B" (an algebra-based Advanced Placement course) and "Physics." Students planning to pursue physical science in college usually took the AP course instead of, rather than subsequent to, regular Physics. As a result, Andy's Physics class contained students who at a larger high school might have been divided into three levels of "honors," regular, and lower-track courses.

[17] Here we describe what took place in the California class. The Virginia version of the lab proceeded similarly but with different equipment.

[18] Since these labs carefully guide students through the refinement process, it's possible that their success on the labs indicates only that they activated *metacognitive* resources for refining prior knowledge, not *epistemological* resources for understanding the knowledge game in which they were engaged. And there's no guarantee that the class discussion, even with its explicit focus on epistemology, activated and solidified the relevant epistemological resources. So, we lack direct evidence that these particular labs activated epistemological "refinement" resources. However, the pre-post epistemological assessments we discussed below suggest that these courses as a whole nudged students toward a more "constructivist," less "transmissionist" view of learning physics.

[19] In Virginia, Andy's students outperformed the school average on the objectively-graded sections of the shared midterm examination. In addition, his students' FCI post-test average was 84%, comparable to the post-test scores of Harvard students (Hake, 1998). Although Andy's students did not take the FCI as a pre-test, an independent sample of 250 Physics students in the same high school achieved an average pre-test score of 32%.

[20] See www.physics.umd.edu/perg/role/ for further information on the "Learning How to Learn Science" project by the University of Maryland Physics Education Research Group (NSF REC: 0087519), which focuses on developing strategies for addressing student epistemologies in large-lecture introductory courses.