

## More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research

David Hammer

Citation: *American Journal of Physics* **64**, 1316 (1996); doi: 10.1119/1.18376

View online: <http://dx.doi.org/10.1119/1.18376>

View Table of Contents: <http://scitation.aip.org/content/aapt/journal/ajp/64/10?ver=pdfcov>

Published by the [American Association of Physics Teachers](#)

### Articles you may be interested in

[Physics educators need to become more knowledgeable about and involved in renewable energy](#)  
*Phys. Teach.* **48**, 86 (2010); 10.1119/1.3293651

[Knowledge Per Se is Still Reason to Fund Research](#)  
*Phys. Today* **46**, 9 (1993); 10.1063/1.2809056

[Test ban hinges on more than seismic research](#)  
*Phys. Today* **36**, 70 (1983); 10.1063/1.2915363

[A course in analytical reasoning: more specific than general](#)  
*Phys. Teach.* **18**, 546 (1980); 10.1119/1.2340605

[Student Misconceptions](#)  
*Am. J. Phys.* **11**, 227 (1943); 10.1119/1.1990482



American Association of **Physics Teachers**

Explore the **AAPT Career Center** –  
 access hundreds of physics education and  
 other STEM teaching jobs at two-year and  
 four-year colleges and universities.

<http://jobs.aapt.org>



# More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research

David Hammer<sup>a)</sup>

Department of Education, Tufts University, Medford, Massachusetts 02155

(Received 25 September 1995; accepted 6 January 1996)

This article analyzes an excerpt of a discussion from a high school physics class from several different perspectives on students' knowledge and reasoning, illustrating a range in what an instructor might perceive in students' work and take as tasks for instruction. It suggests a view of current education research as providing perspectives to expand, refine, and support instructors' perceptions and judgment, rather than as providing definitive principles or proven methods.

© 1996 American Association of Physics Teachers.

## INTRODUCTION

There are often articles in *The American Journal of Physics*, *Physics Today*, and *The Physics Teacher* that review results of physics education research and suggest implications for instruction.<sup>1-3</sup> Writing mainly for readers more familiar with research in physics than in education, the authors sometimes make it a point to temper their claims with qualifications regarding current understanding of student knowledge and learning. Thus, Reif<sup>4</sup> wrote of the prospects that "education might...become more of an applied science," but warned that "it would be foolish to claim that [current results of education research] are more than beginnings." More recently, Redish<sup>2</sup> noted the absence of a unifying theoretical framework and set out to begin one, grouping results into "four broad principles." But, he cautioned, the principles are "fuzzy" and should not be treated "as 'theorems' or as 'laws of cognitive science.'" Redish avoided calling education research "science," and he presented his framework as a "personal account" rather than as formal argument.

This modesty is appropriate: Physics education research has not produced any theories with the precision, coherence, and stability that have been achieved in physics. In fact, it is cause for concern when those who follow or participate in education research accept its results as established. It has, for example, been popular to base instructional decisions on the notion that reasoning abilities develop in stages from "concrete" to "abstract"; today it is often accepted as a truth that students come to physics courses with "misconceptions" that constitute obstacles to learning. These ideas may be useful, but they do not merit faithful commitment in instructional practice: There are a number of reasons to question such views of the development of reasoning abilities<sup>5</sup> and of the structure of intuitive knowledge.<sup>6,7</sup>

Nevertheless, although physics education has not achieved what physics has achieved, it has made substantial progress, and this includes clear, compelling evidence to discredit traditional methods and convictions. Unfortunately, whereas Reif, Redish and other researchers take pains to qualify their claims, many physics instructors remain confident in intuitions borne out of their extensive but unstudied experience as students and as teachers. Both Reif and Redish noted a contrast between the careful thought physicists apply to physics and the "seat of the pants"<sup>8</sup> approach many take to teaching. Like the intuitions physics-naïve students have developed

from their extensive, unstudied experience of the physical world, and in which they may be confident, these instructors' intuitions are inadequate and often incorrect.

Physics education researchers are thus torn by competing and legitimate concerns of, on the one hand, acknowledging limitations in the dependability and precision of their results, and, on the other, promoting their work to the teaching community. Some authors, worried that physics instructors would be disinclined to attend to hesitant, qualified claims, have chosen to present results in more definitive terms than are warranted. Their worry is valid, but their strategy is dangerous: It may contribute to instructors' distrust and disregard of education research; or, possibly worse, some instructors may accept the results at face value.

Part of the problem may lie in what the physics education community expects of research, based largely on experiences with physics research, and of how it should inform instructional practice. We tend to assume that, to be useful, research should provide unambiguous, demonstrably valid results, reliable principles and methods, and in terms sufficiently precise so as not to be sensitive to interpretation and judgment. These assumptions might be appropriate if education were already an applied science—we expect physicists to provide engineers with precise, reliable results on which to base their designs<sup>9</sup>—but it is not. We describe students as having "misconceptions," but we cannot present that account with anything like the precision and confidence with which, for example, we can describe the properties of hydrogen.

It is possible that these assumptions will never be appropriate for education, that fundamental, epistemological differences between the study of human cognition and the study of the physical world will preclude a physicslike formalism in education.<sup>10</sup> It is also possible that education, like physics, will eventually achieve a productive formalism. In either case, whether education is in the very early stages of its evolution into a formal science or whether it will develop a different epistemology, we need to reconsider what to expect of current education research and how it might contribute to physics instruction.

The purpose of this article is to propose a view of education research as providing perspectives that expand, refine, and support instructors' perceptions and judgment, rather than as providing definitive principles or proven methods. Redish suggested such a role in his account:

[Ideas from education research] cannot provide us with hard and fast rules for what to do... But I have found that they help me to organize my thinking about my

students and to refocus my attention. Instead of concentrating only on the organization of the physics content, I now also pay attention to what my students are doing when they interact with a physics course.”<sup>11</sup>

In this article, I focus on the influence of perspectives from research on how instructors organize their thinking and attend to what their students are doing. In the following section, I will present a brief excerpt of conversation from an introductory physics class. I will then discuss several different ways an instructor might perceive the students’ knowledge and reasoning in that excerpt, taking in turn five perspectives from education research.

## MULTIPLE PERSPECTIVES ON A MOMENT FROM A PHYSICS CLASS

During the 1992–1993 school year, I taught a noncalculus, introductory physics course as a guest at a public high school in an eastern Massachusetts city. I videotaped every session from the third week of school through April 1, except for occasional losses due to technical problems, and I recorded daily, detailed notes. The class met every morning from 9:18 to 10:00, except on Monday when it met for a double period. There were 22 students, mostly seniors, divided evenly by gender.

The excerpt below recounts three minutes from a class debate, as transcribed from the videotape, that lasted roughly 33 mins and took place two months into the year. The students were discussing whether a ball rolling on a level plane would keep moving at a constant speed, having heard arguments by Galileo that under ideal conditions it would. I have chosen to present this excerpt for several reasons: First, in this moment the students first articulated the notion that a force is needed to “make the ball move,” an idea that connects to a rich body of research on student conceptions. Second, the substance of the students’ comments is not unusual; similar exchanges occur in almost any introductory physics course, whether high school, university, or even grade school, when students speak about their understanding. Third, this debate was one of the first times in the year the students participated in such a lively, extended discussion.

There is not space here for a more complete account of the debate or of previous class meetings.<sup>12,13</sup> This is a disadvantage with respect to perceiving different aspects of the students’ knowledge and reasoning, as it provides only a glimpse of what was happening in the course. The students’ participation in any three minutes will reflect (or break) patterns that are only noticeable over longer periods. For this reason, I am presenting this excerpt to provide a focus for the subsequent analysis, but I will also refer to the rest of the debate and to previous meetings.

### A moment from a physics class

Prior to this moment, the debate had mostly focused on the question of whether it is friction, gravity, or both that causes the ball to slow down. The students also debated whether it is appropriate to neglect friction or gravity, or both, and whether it is possible to neglect one without neglecting the other.

About 20 min into the debate, Ning<sup>14</sup> argued that Galileo’s ideal conditions would mean no forces on the ball, including no friction and no gravity; and, she claimed, “if you don’t put any force on it, it’s going to stay still or go at constant speed.” Bruce elaborated on Ning’s statement, adding that there must be a force to make the ball move:

*Bruce:* If there is no gravity and no friction, and there is a force that’s making it move, it’s just going to go in a straight line at a constant speed... What’s making the ball move?

*Amelia* [over several other voices]: The forces behind it.

*Susan:* He [Galileo] said there was no force.

*Bruce:* If there’s no force pulling it down, and no force slowing it down, it would just stay straight.

*Harry:* The ball wouldn’t move.

*Jack:* There’s no force that’s making it go.

*Steve:* The force that’s pushing it.

*Bruce:* The force that’s pushing it will make it go.

*Jack:* Where’d that force come from, because you don’t have any force.

*Steve:* No there is force, the force that’s pushing it, but no other force that’s slowing it down.

[Many voices at once, unintelligible. Sean says he has an example.]

*Teacher:* Sean, go ahead with your example.

*Sean:* If you’re in outer space and you push something, it’s not going to stop unless you stop it.

*Teacher:* If you’re in outer space and you give something a push, so there’s a place with no gravity—

*Sean:* No gravity, no friction.

*Teacher:*—it’s not going to stop until you stop it. So Penny what do you think about that?

*Penny:* But we talked about the ball on [a surface], but when we talk about space, it’s nothing like space. So I was just saying that gravity will make it stop.

Amelia objected to Sean’s example for another reason, saying that something moving in space will still stop:

*Amelia:* No. Maybe there’s no gravity and no air there, but there are other kinds of gases that will stop it.

*Teacher:* But those are other, those are outside things.

*Amelia:* The outside friction should stop it.

*Bruce:* That’s not, that makes it an un-ideal state.

*Sean:* Space is a vacuum. Like a vacuum there’s no—

*Amelia:* There are other kinds of gases.

[Several voices, unintelligible.]

*Harry:* We’re talking about ideal space. (students laugh)

I intervened at this point to steer the discussion away from the question of whether there are gases in space and toward the question of whether there is a “force that’s moving” the ball:

*Teacher:*... So how can one side say there are no forces on it, and the other side say there is a force that’s moving it.

*Bruce:* Well there was an initial force.

*Susan:* There’s an initial force that makes it start, giving it the energy to move.

## Multiple perspectives

What instructors perceive in moments such as this depends critically on the conceptual resources they have available and influences strongly how they think to intervene. For example, a principal conceptual resource for all physics instructors should be an understanding of physics; this resource allows them to recognize the correctness of the students’ statements with respect to, in this case, Newtonian

mechanics. Most instructors have a variety of other conceptual resources as well, concerning students' level of effort, interest in the material, self-confidence, study habits, and so on. What they notice in these regards informs their decisions, such as whether to slow down the presentation, which topics to cover or problems to assign, and how to advise particular students. For many instructors, developing these resources happens spontaneously, as a by-product of experience as students and as teachers; for others it is a deliberate process, involving careful thought and, often, informal or formal experimentation.

In the following, I will discuss various aspects of what an instructor might perceive in the preceding excerpt, and I will organize the presentation in terms of conceptual resources an instructor might bring to bear. With the exception of the instructors' knowledge of physics, the resources I will consider correspond to various perspectives developed in education research. This is not to suggest that instructors could not develop similar resources without education research; to the contrary, I expect that thoughtful instructors perceive much of what these perspectives reveal, though perhaps not in such explicit terms. It is to suggest that education research can contribute to that development. For some instructors, a research perspective may lead to new perceptions; for others, it may provide a means to articulate and refine ideas that had been mostly tacit.

For purposes of exposition,<sup>15</sup> I divide the resources into two groups of three. The first group concerns what is traditionally understood as the content of a physics course, namely, knowledge about physical phenomena. It includes Newtonian mechanics, misconceptions, and diSessa's "p-prims."<sup>16</sup> The second group concerns some other aspects of "thinking like a physicist," including reasoning abilities, epistemological beliefs, and inquiry practices. In each case, except for Newtonian mechanics, I will provide a brief review of the perspective, and I will describe what an instructor might perceive in applying the perspective to the debate excerpt.

### Some further caveats

Before proceeding, I would like to forestall several possible misunderstandings about this set of conceptual resources. First, to use any one does not necessarily preclude using others as well, either at the same moment or at other times. At any given moment, some perceptions will be mutually inconsistent, and others will be complementary. An instructor will sometimes choose, tacitly or explicitly, which perspectives to apply, but this is not the same as choosing which perspectives to retain among her or his resources.

Moreover, I do not present this as either a comprehensive or an adequate set of resources, and I do not presume to describe everything an instructor could or should perceive. Nor am I presenting them in order of what I consider increasing validity or sophistication; within each group they are in order of what I am guessing to be decreasing familiarity.

Finally, for the purposes of this analysis I will assume a close correspondence between *perspectives* and *conceptual resources*. In general, one should distinguish between conceptual resources an instructor has developed, resources "in the instructor's head," from public, articulate perspectives. For example, an instructor has his or her *understanding* of Newtonian mechanics as a resource, which should be distinguished from Newtonian mechanics as a body of knowledge.

I will return to this issue in the closing section, but until then I will treat public, articulate perspectives as equivalent to personal conceptual resources.

## Knowledge about physical phenomena

### *Newtonian mechanics*

All physics instructors should have an understanding of the established body of physics knowledge as a principal conceptual resource. In this case, an understanding of Newton's Laws would allow an instructor to recognize the correctness or incorrectness of students' statements.

Some of what the students said in this moment of discussion was correct, namely their assertions that the ball will continue at a constant speed in the absence of any force to make it slow down. Much of what they said was incorrect, in particular that there must be a force on the ball to make it move. In some respects, then, the students appeared to be on the right track; in other respects they were confused. They were incorrect that Galileo's ideal conditions required no gravity; Penny was incorrect in her comment that what happens with a ball rolling has nothing to do with what happens in space. Susan's comment at the end sounds consistent with the idea that an initial force does work on the ball: "There's an initial force that makes it start, giving it the energy to move."

Elsewhere in the conversation, of course, students said many other things that were correct (e.g., Ning later explained that "we don't have to talk about gravity" because the level surface exerts an upward force on the ball equal and opposite to the downward force of gravity) and incorrect (Susan and Nancy contended that "if you're farther away from the ground, the stronger the pull [of gravity]").

Without question, an instructor's understanding of Newton's laws is a powerful and essential resource. However, it concerns only physical phenomena and statements about physical phenomena; it does not concern the nature of student knowledge. With this resource alone, an instructor may be limited to perceiving students' statements as correct or incorrect.

### *Misconceptions*

Among those who follow or participate in science education research, it has become standard to accept that students come to courses with conceptions that differ from scientists' and must be addressed in instruction.<sup>17-19</sup> These conceptions are referred to variously as "preconceptions," "alternative conceptions," and "misconceptions," but the core idea is of *conceptions* that (i) are strongly held, stable cognitive structures; (ii) differ from expert conceptions; (iii) affect in a fundamental sense how students understand natural phenomena and scientific explanations; and (iv) must be overcome, avoided, or eliminated for students to achieve expert understanding. For the purposes of this paper, I will use the most common term, "misconceptions," defined by these four properties.<sup>20</sup>

This perspective reflects the constructivist tenet that people perceive and interpret the world through their current knowledge. It is an alternative to the generally tacit assumptions that students are simply ignorant and that instruction constitutes a transfer of information. By those assumptions, for instance, an instructor might expect students will understand a statement that "an object moves at constant velocity in the absence of external forces," to the instructor a

straightforward expression of the law of inertia; and the instructor might believe that demonstrations of inertia—air track or dry ice carts, yanking a tablecloth, etc.—would be effective in convincing students of the truth of that statement.

From the misconceptions perspective, students are not simply ignorant: They have knowledge about the physical world; their knowledge is reasonable and useful to them; and they use that knowledge to understand what they hear and see. A number of accounts in the literature<sup>17–19</sup> attribute to students, in one form or another, a conception that *motion is caused by force*, in other words, the notion that if an object is moving then there must be a force on it causing that motion. Students with this misconception could understand the instructor's explanation to say, "if the only force on an object is its velocity, then the object keeps moving"; they could see an air-track as demonstrating the need for a cushion of air to maintain the cart's motion.

*Motion is caused by force* is evident in the excerpt of discussion presented above, in statements by Bruce, Amelia, Jack, Harry, and Steve, all of whom spoke of a force as necessary to cause motion. Susan's comment at the end, although to a physicist literally correct, could be seen as indicating a version of this misconception as well: It is unlikely that Susan, using the words force and energy, meant by them what a physicist would mean. From this perspective it is more likely that she was describing a naive impetus theory,<sup>18</sup> according to which motion is caused by an internally stored impetus that is drained from objects by the influences of friction and gravity. This same naive theory could be seen as underlying Susan's and others' beliefs, expressed earlier in the discussion, that gravity causes the ball to slow down.

An instructor who perceives *motion is caused by force* as underlying the students' reasoning would, accordingly, see it as necessary to overcome, because their holding this misconception would interfere with their developing a Newtonian understanding. This overcoming would generally involve first, drawing out explicit statements of the misconception by the students; second, confuting the misconception with arguments and evidence; and, third, promoting new, more appropriate conceptions.<sup>19</sup> One could see this process as beginning in the excerpt above: Students have expressed the misconception, and Sean has started to challenge it with his account of what happens to an object in space.

### P-prims

Despite its wide acceptance in the science education community, there are a number of reasons to question the completeness and validity of the misconceptions perspective. Among the concerns raised, Smith, diSessa and Roschelle<sup>7</sup> have argued that the misconceptions perspective, "in focusing only on how student ideas conflict with expert concepts...offers no account of productive ideas that might serve as resources for learning."<sup>21</sup> If students construct new understandings out of their current knowledge, then there must be aspects of their current knowledge that are useful for that construction.

diSessa<sup>22</sup> has developed an alternative account of intuitive physics knowledge involving "phenomenological primitives" or "p-prims." Rather than describing students' knowledge in terms of conceptions inherently inconsistent with expert knowledge, this perspective posits knowledge elements that, appropriately organized, contribute to expert understanding. By diSessa's account, attributing to students

the misconception *motion is caused by force* confuses emergent knowledge, an act of conceiving in a particular situation, for a stable cognitive structure. If *motion is caused by force* were a stable cognitive structure, then students should attribute a force whenever they see a motion. But he and others<sup>23</sup> have argued, students are not consistent in this way: whether they infer a force seems to be sensitive to the particular context in which they see motion.

On this account, students' reasoning can be understood in terms of the activation of the p-prim *maintaining agency*.<sup>24</sup> Whereas the misconception is an element of cognitive structure specifically tied to motion and force, *maintaining agency* is posited as an element of cognitive structure involved in an intuitive understanding of any continuing effect maintained by a cause: For example, an engine maintains the motion of a car; a supply of energy keeps a bulb lit; or continuous encouragement keeps a student motivated. *Actuating agency* is another p-prim, an element of cognitive structure involved in understanding an effect initiated by a cause, when the effect outlasts the cause: A toss causes the motion of a ball; the strike of a hammer causes a bell to ring; or a traumatic event causes anxiety. Unlike the misconception *motion implies a force*, the p-prims *maintaining agency* and *actuating agency* are not "incorrect." Neither are they correct; they are elements of cognitive structure that can be activated under various circumstances. Development toward expert understanding involves modifying their activation conditions, not replacing them with appropriate structures.

Using this perspective, one may perceive the activation of *maintaining agency*, in the students' references to a force behind the ball causing its motion, and the activation of *actuating agency*, in Bruce's and Susan's references at the end to an "initial force." Rather than see these as interfering with students' construction of expert understanding, an instructor could see *maintaining agency* as a useful resource for building an understanding of *momentum*, *actuating agency* for *impulse*.<sup>25</sup>

Accordingly, the instructor could try to take advantage of the students' intuitive knowledge, adapting it gradually toward Newtonian ideas, rather than try to displace their conceptions to make room for physicists. One could see this discussion as beginning that process, as the teacher's question ("how can one side say there are no forces on it, and the other side say there is a force that's moving it?") seems to have prompted students to distinguish an initial force from a continuing force. Thus, the students were now describing an initial agency imparting something to the ball, possibly a seed for the idea of an impulse imparting momentum.

### "Thinking like a physicist"

The resources I have discussed thus far all constitute or pertain to knowledge about physical phenomena, traditionally seen as the "content" of the physics course. Most physics instructors, however, hope not only that their students will become familiar with the established body of knowledge, but also that they will develop abilities and inclinations to "think like physicists." The latter agenda is especially difficult to pursue, because our understanding of what it means to "think like a physicist" is not nearly as well developed as our understanding of physical phenomena. It is relatively straightforward for a physicist to assess the correctness of the content of a students' statement with respect

to established knowledge, but it is not at all straightforward to assess it with respect to the less tangible goals of promoting scientific reasoning, habits, and attitudes.

In other words, instructors are better equipped with resources to perceive and consider aspects of students' knowledge about physical phenomena than to perceive and consider their reasoning in other respects. This section discusses three perspectives on students' work that may contribute to instructors' resources, concerning reasoning abilities, epistemological beliefs, and inquiry practices.

### *Reasoning abilities*

One may conceive of students not only as having (or lacking) knowledge in various forms about the physical world, but also as having (or lacking) more general abilities for reasoning and understanding.

For example, it has been popular to attribute students' difficulties to their "concrete" rather than "abstract" reasoning abilities: Students who have not developed "abstract" reasoning are seen as incapable of understanding the concepts of physics, such as *force* or *energy*, because these are not directly observable, manipulable objects. This view is ostensibly based on Piaget's<sup>26</sup> account of cognitive development, specifically concerning the progression from concrete to formal operational reasoning, but it is an untenable distortion of those ideas.<sup>27</sup> Because I am not aware of any substantive basis in the research literature for this account of reasoning abilities, I will not discuss it further or attempt to apply it to the excerpt.

There, however, are a number of more useful and supported accounts of reasoning abilities.<sup>28</sup> Here I focus on one developed by Kuhn<sup>29</sup> that is closely related to Piaget's work, specifically in regard to the development of abilities to reflect on one's own thinking. By Kuhn's perspective, scientific reasoning involves and develops from abilities for argumentation, including abilities to identify and evaluate different points of view. She argues that these abilities are not ordinarily involved in everyday thinking and that they are often not sufficiently developed in many children and nonscientist adults. Thus, for example, when asked to defend a conjecture against counter evidence, many students simply reiterate the conjecture; when asked to generate hypothetical, contradictory evidence (e.g., "What evidence might someone give to try to show that you were wrong?"), they are unable to answer appropriately. In general, they are unable to coordinate and distinguish alternative theories and evidence. Rather, they meld theory and evidence into a single "script" they take for granted as describing reality.

Taking this perspective, one might perceive the students in the excerpt as lacking the abilities Kuhn describes. The students were not, here or for most of the debate, trying to delineate different points of view; they were simply making assertions, reiterating and elaborating their respective scripts. Sean, for example, asserted that an object in outer space "is not going to stop"; Amelia objected that there are still "gases that will stop it"; and Sean contradicted her, saying that "space is a vacuum." Neither student reflected on the relevance of their disagreement to the question of whether an object will move at constant velocity in the absence of friction.

Earlier in the debate, challenged to support her assertion that gravity causes the ball to slow down, Nancy could only restate her claim:

*Nancy:* If you roll a ball down it speeds up because of gravity. And if you roll a ball up, it slows down because of the gravitational pull. So if you're rolling a ball horizontally the gravitational pull is pulling it down and it slows it down, you just can't notice, but eventually it will stop.

Steve, similarly defending his position that it is friction and not gravity causing the ball to slow down, could only restate his claim:

*Steve:* But if there was no friction and there was still gravity then it wouldn't slow down, because the ball wouldn't have any friction. It doesn't matter, gravity doesn't make it slow down. The thing that makes it slow down is the friction, not the gravity.

With respect to Newtonian mechanics, Steve was correct and Nancy was not. With respect to Kuhn's account of scientific reasoning, neither of them was able to give valid evidence or argument.

There were also some examples of students' successfully coordinating alternative points of view and evidence. Jack, in this excerpt, might be seen as showing an awareness of different points of view, as he implied there was an inconsistency within the idea that there are no forces on the ball except a force that's making it move: "Where'd that force come from, because you don't have any force."

Ning clearly displayed such abilities earlier in the class. I had asked the students to rebut Galileo's view that "any velocity once imparted to a body will be rigidly maintained as long as there are no causes of acceleration or retardation."<sup>30</sup> In response, Ning asked me to walk across the room, varying my speed and looking at her as I walked. Relative to me, she explained, she was speeding up and slowing down, but there was nothing to cause her to speed up or slow down. Having given this argument, she then offered to refute it herself.

Perceiving students in this way, an instructor might make different decisions about how to proceed than if she or he saw them only through traditional content-oriented perspectives. In particular, the instructor may choose to focus on developing students' abilities to participate in scientific argument, perhaps by pressing them to articulate alternative points of view and systematically derive their consequences; the instructor might design or locate materials to promote students' abilities to coordinate alternative points of view and evidence.<sup>31</sup> Or, the instructor might decide that some of these students are not ready to learn Newtonian mechanics and seek to develop the prerequisite reasoning abilities using less difficult content.

### *Epistemological beliefs*

How students reason in a physics course may reflect not only whether they have or do not have certain abilities, but also what they believe about the course and the knowledge and reasoning it will entail.<sup>32,33</sup> Students may fail to coordinate alternative theories, for example, not necessarily because they lack the requisite abilities, but because they do not see a science class as a place to consider multiple points of view.

I have argued<sup>33</sup> that some students could be characterized as believing (1) that understanding in physics means being familiar with a collection of facts and formulas; (2) that the formalism of physics is only loosely associated with concep-



tual content or with what happens in the “real world;” and (3) that learning physics means memorizing information and procedures supplied by the professor or textbook. In contrast, other students could be characterized as believing (1) that understanding in physics means developing a sense of its underlying principles and coherence; (2) that the formalism of physics represents ideas about the physical world, including everyday experience; and (3) that learning physics is a process of applying and modifying one’s own understanding.

By this perspective, an instructor could see the students’ participation in the excerpt as reflecting their beliefs about knowledge and learning in the course. That this was one of the first times in the year the students participated in such lively, extended debate, arguing among themselves without looking to the teacher as the source of understanding, might be seen as indicating change in their epistemological beliefs: They were starting to see their own ideas as relevant and to expect that they should be thinking things through for themselves.

The exchange between Sean and Penny might be understood in terms of a difference of belief with respect to the coherence of physics knowledge. Sean felt there should be consistency at some level between what would happen “if you’re in outer space and you push something” and what happens to a ball rolling on the earth, but Penny did not, saying that the rolling ball is “nothing like space.” Other students, including Amelia, believed with Sean that there should be a coherence in their understanding of the two situations, but they disagreed with him about the substance of that understanding.

These perceptions, again, would lead to further considerations for an instructor.<sup>34</sup> One may choose, for example, to focus directly on establishing appropriate beliefs about the coherence of physics understanding, such as by supporting students’ attempts to coordinate different aspects of their experience or by explicitly emphasizing coherence as an objective. It becomes apparent, moreover, that a range of perceptions of students, and consequent intentions for instruction, can lead to dilemmas over how to proceed.<sup>35</sup> There could be a dilemma here, for instance, for an instructor who sees in these students both misconceptions, about the relationship between forces and motion, and nascent epistemological beliefs, about the relevance of everyday knowledge and personal sense-making. On the one hand, the instructor would feel obliged to challenge the misconceptions; on the other hand, to challenge those misconceptions at this point may have the unintended effect of re-establishing students’ convictions that they should not try to think for themselves.

### *Inquiry practices*

Thus far, all of the perspectives I have considered attribute statements and actions to students as individuals. One might also conceive of collective phenomena among the class as a whole. For example, rather than understand students’ success or failure to coordinate alternative theory and evidence as reflecting either individual abilities or beliefs, one may think of the ways in which these practices of argumentation have or have not emerged in the context of the class. Or, rather than understand the students’ participation in this debate as reflecting changes in individual epistemologies, one may see it as an essentially social phenomenon that came about as a result of various aspects of the situation of the class on that day.<sup>36</sup>

By this view, students and physicists participate in socially constructed, situated practices.<sup>37,38</sup> Scientific knowledge and practices are collective constructs of the scientific community.<sup>39</sup> Fundamentally, learning physics means becoming a member—and adopting the practices—of the community of physicists,<sup>40</sup> in much the same way that one becomes a member of any new culture. There is not necessarily any normative rationality to these practices: To members, they are natural and routine; to outsiders, they can seem quirky and arbitrary.

There are various versions of this perspective. Lave and Wenger’s<sup>37</sup> account, with roots in anthropological research, refrains from attributing conceptions, beliefs, or abilities to individuals. Other versions have arisen more from Vygotsky’s developmental psychology,<sup>41</sup> by which individual reasoning processes are internalized forms of social interaction. In this manner, consistent with Kuhn’s account,<sup>29</sup> one may understand students to develop abilities for coordinating theories and evidence by internalizing forms of argument they first experience as social practice. Epistemological beliefs may similarly be seen as following, and influenced by, changes in practice.<sup>42</sup> This is the reverse of the traditional view that individual knowledge and abilities are prerequisites to participation in scientific inquiry; by this account, the participation comes first.

To return to the students’ debate, it is routine among physicists, in certain circumstances, to suppose ideal, unattainable conditions, in other words to neglect aspects of what they see happening. This practice was part of Galileo’s assertion that “any velocity once imparted to a body will be rigidly maintained as long as there are no causes of acceleration or retardation, a condition which is approached only on horizontal planes where the force of friction has been minimized.”<sup>30</sup> Implicit in Galileo’s claim is that such conditions are never actually realized: He was deliberately reasoning about a situation he felt could not occur. To nonphysicists, including these students, it may be difficult to understand this practice or when and how it should be invoked.

In the excerpt above, Amelia objected to Sean’s thought experiment in space because, she claimed, even in space there is some friction. Earlier, several students took the position that it would not be possible to eliminate friction with the ground without also eliminating gravity; this reasoning may have contributed to the confusion evident in the excerpt over whether Galileo’s ideal conditions involved neglecting gravity. In the context of a discussion of the Second Law of Thermodynamics, a physicist would agree: It is not possible to eliminate friction between the ball and the ground without eliminating the force of contact between them; more generally, it is not possible to eliminate friction absolutely under any (classical) circumstances, even in space. But in this context, reasoning about the ball on the ground or in space, it would be routine for a physicist to neglect friction. Harry’s joking response to Amelia (“We’re talking about ideal space.”), and the laughter it drew, highlighted that this practice of assuming ideal conditions was not natural or routine for the class.

In other respects, the class’s inquiry practices resembled physicists’, such as in their use of analogies<sup>43</sup> and references to prior experience. Sean’s comparison to outer space was an example; elsewhere in the discussion students referred, for example, to their experiences throwing balls, swinging pendulums, and playing air hockey.

These perceptions might lead an instructor to try to draw the class into the physicists' practices of assuming ideal conditions, and to build on their use of analogies and comparisons. Sherin, diSessa, and Hammer<sup>44</sup> discussed the activity of programming a simulation of a Newtonian object. The students collaborated, in a teacher-moderated discussion, in the design of an algorithm to control the motion of the "space ship" of a computer game. We argued that this construction of a computational model contributed to a situation in which an appropriate practice of idealization was likely to emerge for the students, in contrast to a discussion focused on the question of what "really" happens to a moving object.

In general, this perspective provides alternative possibilities for diagnosing students' strengths and needs, and for assessing their progress, other than in terms of individually held knowledge and ability. Thinking of students' participation in terms of situated, collective phenomena, an instructor would not, for example, necessarily expect the difficulties or achievements students' display in one situation to persist in others. As well, rather than directing interventions exclusively or primarily at individual knowledge and abilities, an instructor might think of the task of establishing certain social practices as prerequisite to individual learning.

## EDUCATION RESEARCH AND INSTRUCTORS' CONCEPTUAL RESOURCES

Discussing college teaching 25 years ago, Perry<sup>45</sup> described what is probably a familiar situation among physics instructors:

The good teacher becomes one who supports in his students a more sustained groping, exploration, and synthesis... Typically, [instructors] enter their classrooms with [this] set of values, looking at the [class] as an opportunity for the students to develop initiative and scope in their own thinking. No sooner do the students get started, however, and some error or inexactness is voiced, than the older form of responsibilities imposes on the instructor the imperative of "correcting." In the hours where this tendency gets in motion, three to five corrections of this kind appear sufficient to defeat the students' initiative for search and the flow of their exploration. The initiative for conversation then falls back upon the instructor, who then finds himself in a monologue or lecture...compelled...to do what he had never intended to do.<sup>46</sup>

Part of the difficulty is that the "errors" and "inexactnesses" are so salient. For a physics instructor who understands Newtonian mechanics, for example, it is relatively automatic and straightforward to assess the correctness of what students say about forces and motion; it may not be so automatic or straightforward to consider the value of their "groping, exploration, and synthesis." My purpose in this article has been to illustrate how perspectives from education research might influence what instructors perceive in their students.

I have recounted a moment from a physics class discussion and analyzed it from several perspectives. I have not presented this as a comprehensive set, nor as a progression of increasingly adequate theories. Certainly there are many other considerations I have not addressed here, including, to name a few, students' mathematical abilities and use of the formalism, gender differences, or anxieties about learning

science. I have only intended to present a sampling of conceptual resources. Equipped with a range of such resources, instructors would see much more than "errors" and "inexactnesses."

On this view, teachers are constantly making choices, whether implicitly or explicitly, of how to perceive what their students are doing and of how to respond to those perceptions. I noted some examples above: Listening to the students talk about forces and motion, an instructor may choose to perceive either misconceptions or the activation of p-prims. Or, perceiving both misconceptions and the beginnings of independent reasoning, an instructor may experience a dilemma over whether to challenge the former or to promote the latter. How instructors do or should handle these choices and dilemmas is a matter for further discussion and study;<sup>35</sup> for the present, I hope to have suggested the range in what an instructor might perceive in students, diagnose as their strengths and needs, and see as tasks for instruction.

This role of education research in physics instruction is an alternative to the traditional relationship between research and application, and it raises a different agenda for further work.

(1) *Distinguish the goal of developing a coherent theoretical framework from the goal of improving (current) physics education.* I am by no means advocating complacency with respect to furthering our understanding of the process of physics education. It is essential that researchers seek coherent, principled frameworks, and growth in this regard often emerges from researchers committed to developing a particular perspective. As Reif noted, no one should "minimize the long-term potential of principled analytic approaches."<sup>47</sup> Even in the near-term, such approaches are yielding useful new ideas and materials.

At present, however, education research has yet to achieve theories with the precision, coherence, and stable consensus that would warrant faithful commitment by instructors. To the end of improving current physics education, researchers and instructors should be cautious about promoting or accepting what "research has shown." Because we do not yet have any proven methods or clear principles—education is not yet an applied science—we must continue to rely substantially on instructors' perception and judgment. I am suggesting we think of the current contributions of education research primarily in terms of how it might influence that perception and judgment.

A reviewer suggested I discuss the Force Concept Inventory (FCI)<sup>48</sup> a subject of current debate.<sup>49</sup> The disagreement concerns what, precisely, the FCI measures, in particular whether an FCI score measures a student's understanding of the Newtonian concept of *force*. There is wide agreement that a low score shows a lack of understanding of the concept, and that low scores on the test provide solid evidence to discredit conventional methods, but it remains controversial what may be concluded from a high score.

This debate provides a topical context for distinguishing goals of physics education research. For the goal of developing a principled framework, the debate is productive in that, for one, it may lead toward a shared and technically precise definition of what constitutes "understanding a concept." For the goal of improving current physics education, I am suggesting that the FCI can and should inform instructors' work, especially to challenge conventional intuitions about learning and methods of instruction. It provides an alternative lens through which to consider students' progress, and



the view through that lens should influence instructors' perception and judgment. But I am also suggesting that we do not yet have a shared, precise definition of what constitutes understanding, and it would not be appropriate for instructors to treat FCI scores as unproblematic, objective measurements.<sup>50</sup>

(2) *Cultivate a stance of inquiry in instruction.* In sum, it is essential that researchers and instructors maintain an appropriate humility with respect to what we understand about the process of education. For researchers, this means tempering claims of implications and prescriptions for instructional practice. For instructors, this means adopting a stance of inquiry, regarding the process both in general and in particular students. Physics instruction should be understood to involve ongoing inquiry into students' knowledge and abilities, assessment and reassessment of their strengths and needs, and considered experimentation with different methods of intervention.

One entailment of this view is that instructors need information about their students' knowledge and reasoning; and this information should come in various forms, because there is not an adequate framework by which to design a focused collection. The variety should include traditional short-answer problems and standardized multiple choice instruments. It should also include, for example, written explanations of problems or of physical principles; nontraditional, open-ended problem solving; and, as this paper presented, discussions and debates during class or recitation sections. Learning to teach should involve developing the skills of gathering information, including the skills of moderating discussions and "interviewing" students regarding their understanding. On this view, activities such as the discussion presented above are valuable not only pedagogically but also as part of the instructor's investigation into the students' knowledge and reasoning.<sup>51</sup>

A second entailment of this view is the need to create forums for conversation among instructors. Across all educational levels, from preschool to university, there are few occasions for substantive exchange about learning and instruction. There is a general sense that everyone is both entitled and responsible to develop their own ideas, and there is little opportunity or obligation to support those ideas or to explore others. There are, however, some impressive examples of progress. Nelson and Hammerman<sup>52</sup> and their colleagues have promoted a "culture of inquiry" among teachers in elementary mathematics: "Inquiry groups" of a dozen teachers and a facilitator meet, for two hours every other week from September to June, to discuss issues in learning and instruction, focusing on the teachers' ongoing classroom experiences. Feldman<sup>53</sup> has pursued a similar agenda with high school physics teachers conducting more deliberate "collaborative action research."

It would be productive to establish similar forums at all levels, including colleges and universities. Of course, there are obstacles that will be difficult to overcome; principal among these are institutional and cultural attitudes toward teaching as having little intellectual status. I hope with this article to help motivate a view of teaching as, among other things, an intellectually subtle and demanding enterprise.

(3) *Develop a variety of conceptual resources, in addition to technical resources.* Discussions of the contributions of physics education research have generally focused on materials and techniques, including textbooks, curricula, software and equipment, standardized exams, and methodological

prescriptions.<sup>54</sup> There is no question that this work is valuable: Physics instructors at any level need such technical resources, and physics education research has produced a number of excellent resources of this kind.

Technical resources, however, are not sufficient for a physics instructor, any more than they would be for a doctor. A doctor who knows of only one or two diseases would have only one or two options for diagnosing an ailment, regardless of the technical resources available. When the diagnosis happens to be correct, the prescribed treatment may be effective; when the diagnosis is not, the treatment may not only be ineffective, it may be damaging. The same is true in instruction, and, unfortunately, it is not unusual for pedagogical interventions to do more harm than good.<sup>55</sup>

While we do not yet have available an adequate, unified framework, we can be quite confident that physics knowledge and learning involves a range of cognitive, affective, individual and social structures and processes in a complex ecology.<sup>56</sup> Instructors need to have, not only the technical resources for gathering information, but also a range of conceptual resources by which to interpret that information, providing a variety of options for diagnosis. The analysis above, of three minutes from a classroom discussion, illustrates how much there is potentially for an instructor to see and consider.

I am suggesting that there needs to be a emphasis on instructors' conceptual resources, in our conceptions of the contributions of education research, comparable to the emphasis on technical resources. Instructors' professional development, at any level, should address not only on methods and materials but also multiple perspectives on knowledge, reasoning, and learning, to promote flexible awareness of students' strengths and needs. Similar ideas have motivated programs<sup>57</sup> that focus on developing teachers' understanding, of physics as well as of knowledge and pedagogy.

(4) *Develop narrative accounts of authentic episodes of learning and instruction.* It should become standard, common practice among teachers and researchers to exchange and discuss detailed, extended accounts of episodes of physics learning and instruction.<sup>58</sup> These accounts, in written narratives or annotated videotapes, can bridge the gap between research and instruction. They provide specific, authentic cases to clarify and compare different perspectives, instance their claims, and consider their adequacy and relevance. They provide material to draw out instructors' contextual, atheoretical knowledge and experience, to facilitate explicit comparison among teachers' intuitions as well as between those intuitions and the theories articulated in the literature. They provide cases to expose the tensions for instructors among different ways of thinking about students, to study how they manage dilemmas, and to illustrate teaching as a process of inquiry. The use of narrative cases has been promoted for teacher education and generally as an epistemologically sound means of representing and communicating knowledge in education.<sup>59</sup>

(5) *Study instructors' use of perspectives.* I have proposed that perspectives from education research might contribute to instructors' conceptual resources, and I have illustrated what various perspectives would have to say about a particular moment of instruction. I have not, however, discussed whether and how instructors actually make use of the different perspectives.

In particular, it is important to contend with the difference between public, articulate perspectives and personal concep-

tual resources. I noted earlier that I would assume, for the purposes of this article, that these are equivalent. But they are not generally equivalent: Instructors'—and researchers'—understandings of research perspectives vary considerably. Some, for example, understand the misconceptions perspective as detailing "what's wrong" with students' thinking and as implying the importance of anticipating and eliminating their mistaken concepts; others understand it as highlighting the rationality and legitimacy of student thinking and as suggesting the importance of engaging students in extensive exploration of their ideas. This range of interpretation may reflect ambiguity inherent in the perspective itself. For this reason and others, we need to study how any given perspective actually influences what instructors see in students' work, not simply to understand the instructors' abilities to assimilate and apply ideas from research, but to understand the adequacy and validity of those ideas in authentic conditions.

## ACKNOWLEDGMENTS

I am grateful for the support of a Spencer Foundation Postdoctoral Fellowship awarded by the National Academy of Education, and for further support by the Center for the Development of Teaching, at EDC in Newton, MA, from a grant by the Dewitt Wallace-Reader's Digest Fund. I thank Sherry Cook, Andy diSessa, David Hestenes, Barbara Nelson, Fred Reif, Deborah Schifter, and two anonymous reviewers for comments and suggestions on various pieces and drafts of this article.

<sup>a</sup>E-mail address: dhammer@tufts.edu

<sup>1</sup>F. Reif, "Scientific approaches to science education," *Phys. Today* **39**(10), 48–54 (1986).

<sup>2</sup>E. F. Redish, "Implications of cognitive studies for teaching physics," *Am. J. Phys.* **62**(9), 796–803 (1994).

<sup>3</sup>J. Mestre and J. Touger, "Cognitive research—what's in it for physics teachers?," *Phys. Teach.* **27**(9), 447–456 (1989); L. C. McDermott, "What we teach and what is learned—Closing the gap," *Am. J. Phys.* **59**(4), 301–315 (1991); A. Van Heuvelen, "Learning to think like a physicist: A review of research-based instructional strategies," *Am. J. Phys.* **59**(10), 891–897 (1991); F. Reif, "Millikan Lecture 1994: Understanding and teaching important scientific thought processes," *Am. J. Phys.* **63**(17–32), (1995).

<sup>4</sup>Reference 1, p. 53.

<sup>5</sup>K. E. Metz, "Reassessment of developmental constraints on children's science instruction," *Rev. Ed. Res.* **65**(2), 93–127 (1995); U. Wilensky, "Abstract meditations on the concrete and concrete implications for mathematics education," in *Constructionism*, edited by I. Harel and S. Papert (Ablex, Norwood, NJ, 1991).

<sup>6</sup>A. diSessa, "Towards an epistemology of physics," *Cognit. Instruct.* **10**(2–3), 105–225 (1993).

<sup>7</sup>J. Smith, A. diSessa, and J. Roschelle, "Misconceptions reconceived: A constructivist analysis of knowledge in transition," *J. Learn. Sci.* **3**(2), 115–163 (1993).

<sup>8</sup>Reference 1, p. 48.

<sup>9</sup>Some philosophers of science would debate whether this is a valid understanding of what physics has accomplished. See, e.g., N. Cartwright, *How the Laws of Physics Lie* (Oxford U.P., New York, 1983). I assert here only that this is what most physicists and physics instructors expect; I do not enter the debate regarding the validity of such expectations.

<sup>10</sup>For arguments to this effect, see A. V. Cicourel, *Method and Measurement in Sociology* (The Free Press, New York, 1964); and J. S. Bruner, *Actual Minds, Possible Worlds* (Harvard U.P., Cambridge, MA, 1986).

<sup>11</sup>Reference 2, p. 796.

<sup>12</sup>For more complete account of the debate, see D. Hammer, "Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions?," *J. Learn. Sci.* **5** (2), 97–127 (1996).

<sup>13</sup>For an account of activities early in the course, see D. Hammer, "Episte-

mological considerations in teaching introductory physics," *Sci. Ed.* **79**(4), 393–413 (1995).

<sup>14</sup>I am using pseudonyms for the students.

<sup>15</sup>That is, I do not mean to imply any ontological distinctions.

<sup>16</sup>Reference 12 is an extended comparison of the misconceptions and p-prims perspectives using the entire class discussion from which this excerpt is drawn.

<sup>17</sup>J. Clement, "Student preconceptions in introductory mechanics," *Am. J. Phys.* **50**, 66 (1982); I. A. Halloun and D. Hestenes, "Common sense concepts about motion," *Am. J. Phys.* **53**(11), 1056 (1985); D. I. Dykstra, C. F. Boyle, and I. A. Monarch, "Studying conceptual change in learning physics," *Sci. Ed.* **76**(6), 615–652 (1992).

<sup>18</sup>M. McCloskey, "Naive theories of motion," in *Mental Models*, edited by D. Gentner and A. Stevens (Erlbaum, Hillsdale, NJ, 1983), pp. 299–324.

<sup>19</sup>K. A. Strike and G. J. Posner, "A conceptual change view of learning and understanding," in *Cognitive Structure and Conceptual Change*, L. H. T. West and A. L. Pines, ed. (Academic, New York, 1985), pp. 211–231.

<sup>20</sup>Not all authors would agree with this set of properties. In particular, some consider the term "misconceptions" to refer only to the phenomenology of patterns in students' responses to questions (Hestenes, 1994, private communication).

<sup>21</sup>Reference 7, p. 124.

<sup>22</sup>References 6 and 7. For related accounts, see J. Minstrell, "Facets of students' knowledge and relevant instruction," in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg, and H. Niedderer (IPN, Kiel, Germany, 1992), pp. 110–128; D. E. Brown, "Re-focusing core intuitions: A concretizing role for analogy in conceptual change," *J. Res. Sci. Teach.* **30**(10), 1273–1290 (1993).

<sup>23</sup>References 6 and 7, L. Viennot, "Spontaneous reasoning in elementary dynamics," *Eur. J. Sci. Ed.* **1**(2), 205–221 (1979); L. C. McDermott, "Research on conceptual understanding in mechanics," *Phys. Today* **37**, 24–32 (July 1984).

<sup>24</sup>diSessa (Ref. 6) called this p-prim *continuing push*, but the word *push* in that name may be misleading, as the agency need not take the form of a force. I will also use the name *actuating agency* instead of diSessa's *force as mover*.

<sup>25</sup>A. diSessa, "Momentum flow as an alternative perspective in elementary mechanics," *Am. J. Phys.* **48**(5), 365–369 (1980).

<sup>26</sup>J. Piaget, "Piaget's theory," in *Carmichael's Manual of Child Psychology*, edited by P. H. Mussen (Wiley, New York, 1970), pp. 703–732.

<sup>27</sup>References 5 and 7. See the Metz article for a discussion of Piaget's work, including an analysis of how it has been misinterpreted and a review of recent, legitimate challenges to his claims. Wilensky, in Ref. 5, and Smith *et al.*, in Ref. 7, debunked the popular distinction between abstract and concrete.

<sup>28</sup>See especially Reif, 1995, in Ref. 3 and citations therein.

<sup>29</sup>D. Kuhn, "Children and adults as intuitive scientists," *Psych. Rev.* **96**(4), 674–689 (1989); "Connecting scientific and informal reasoning," *Merrill-Palmer Q.* **39**(1), 74–103 (1993).

<sup>30</sup>Quoted in U. Haber-Schaim, J. B. Cross, J. H. Dodge, and J. A. Walter, *PSSC Physics* (D. C. Heath and Company, Lexington, MA, 1976), p. 224.

<sup>31</sup>For example, "vee" diagrams discussed in J. D. Novak and D. B. Gowin, *Learning How to Learn* (Cambridge U.P., New York, 1984).

<sup>32</sup>P. W. Hewson, "Epistemological commitments in the learning of science: Examples from dynamics," *Eur. J. Sci. Ed.* **7**(2), 163–172 (1985); F. Reif and J. H. Larkin, "Cognition in Scientific and Everyday Domains: Comparison and Learning Implications," *J. Res. Sci. Teach.* **28** (9), 733–760 (1991); R. F. Gunstone, "Constructivism and metacognition: Theoretical issues and classroom studies," in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg and H. Niedderer, (IPN, Kiel, Germany, 1992), pp. 129–140.

<sup>33</sup>D. Hammer, "Epistemological beliefs in introductory physics," *Cognit. Instruct.* **12**(2), 151–183 (1994).

<sup>34</sup>The article cited in Ref. 13 focuses on epistemological considerations in analyzing another discussion from this course.

<sup>35</sup>D. Ball, "With an eye on the mathematical horizon: dilemmas of teaching elementary school mathematics," *Elem. Sch. J.* **93**(4), 373–397 (1993); D. Hammer, "Student inquiry in a physics class discussion," *Cognit. Instruct.* **13**(3), 401–430 (1995).

<sup>36</sup>It may be familiar in everyday thought to attribute aspects of someone's behavior to the situation rather than to individual traits, such as in understanding why someone behaves 'like a different person' depending on the particular group of people, the activity, and the setting.

<sup>37</sup>J. S. Brown, A. Collins, and P. Duguid, "Situated cognition and the culture of learning," *Ed. Research.* 32–42 (1989); P. Cobb, "Where is the

- mind? Constructivist and sociocultural perspectives on mathematical development," Ed. Research. **23**(7), 13–20 (1994).
- <sup>38</sup>J. Lave and E. Wenger, *Situated Learning: Legitimate Peripheral Participation* (Cambridge U.P., New York, 1991).
- <sup>39</sup>That I have chosen to present this view under the heading "Thinking like a physicist," rather than under the heading "Knowledge about physical phenomena," may be misleading: Most versions of this perspective would not admit a distinction between these two categories.
- <sup>40</sup>Some versions of this perspective, (e.g., Lave and Wenger, Ref. 38), I should note, seem to leave little room for the possibility of formal instruction: Learning means becoming enculturated in a community, and that can happen only through participation in that community. Such participation does not take place in schools.
- <sup>41</sup>L. S. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes* (Harvard U.P., Cambridge, MA, 1978).
- <sup>42</sup>A. Collins, "The role of computer technology in restructuring schools," *Phi Delta Kappan* **73**, 28–36 (1991).
- <sup>43</sup>J. Clement, "Nonformal reasoning in experts and in science students: The use of analogies, extreme cases, and physical intuition," in *Informal Reasoning and Education*, edited by J. Voss; D. Perkins and J. Siegel (Erlbaum, Hillsdale, NJ, 1991), pp. 345–362.
- <sup>44</sup>B. Sherin; A. diSessa and D. Hammer, "Dynaturtle revisited: Learning physics through collaborative design of a computer model," *Interact. Learn. Environ.* **3**(2), 91–118 (1993).
- <sup>45</sup>W. B. Perry, *Forms of Intellectual and Ethical Development in the College Years: A Scheme* (Holt, Rinehart, and Winston, New York, 1970).
- <sup>46</sup>Reference 45, pp. 211–212.
- <sup>47</sup>Reference 1, p. 53.
- <sup>48</sup>D. Hestenes, M. Wells, and G. Swackhamer, "Force Concept Inventory," *Phys. Teach.* **30**(3), 141–158 (1992).
- <sup>49</sup>For debate concerning what the FCI measures, see D. Huffman and P. Heller, "What does the Force Concept Inventory actually measure?," *Phys. Teach.* **33**(3), 138–143 (1995); D. Hestenes and I. Halloun, "Interpreting the Force Concept Inventory: A response to March 1995 critique by Huffman and Heller," *Phys. Teach.* **33**(8), 502, 504–506 (1995); P. Heller and D. Huffman, "Interpreting the Force Concept Inventory: A reply to Hestenes and Halloun," *Phys. Teach.* **33**(8), 503, 507–511 (1995).
- <sup>50</sup>Contrast, for example, the use of a commercial ammeter: Within well-defined conditions of application, the use of an ammeter can be treated as an unproblematic measurement of electric current, reproducible and independent of individual judgment. I am suggesting that this epistemology is not appropriate for the current state of education research.
- <sup>51</sup>There are a number of suggestions in the literature for discussion-oriented pedagogy in physics instruction, both in high school classes and in college and university courses. See, for example, Van Heuvelen, cited in Ref. 3, and R. R. Hake, "Socratic pedagogy in the introductory physics laboratory," *Phys. Teach.* **30**(9), 546–52 (1992).
- <sup>52</sup>B. S. Nelson, "Reconceptualizing teaching: Moving toward the creation of intellectual communities of students, teachers, and teacher educators," in *Professional Development in an Era of Reform*, edited by M. W. McLaughlin (Teachers College Press, New York, in press).
- <sup>53</sup>A. Feldman, "Teachers learning from teachers: Knowledge and understanding in collaborative action research," Doctoral dissertation, Stanford University (1993).
- <sup>54</sup>See Refs. 1–3 and citations therein.
- <sup>55</sup>For example, Treisman found that remedial programs in mathematics at the University of California at Berkeley, designed with the best of intentions out of the conviction that the students needed further practice in basic skills, were making matters worse. U. Treisman, "Studying students studying calculus: A look at the lives of minority mathematics students in college," *College Math. J.* **23**, 362–372 (1992).
- <sup>56</sup>See Redish's "Individuality Principle," Ref. 2, p. 801; K. A. Strike and G. J. Posner, "A revisionist theory of conceptual change," in *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice*, edited by R. A. Duschl and R. J. Hamilton (State University of New York, Albany, 1992), pp. 147–176; H. Niedderer and H. Schecker, "Towards an explicit description of cognitive systems for research in physics learning," in *Research in Physics Learning: Theoretical Issues and Empirical Studies*, edited by R. Duit, F. Goldberg, and H. Niedderer, (IPN, Kiel, Germany, 1992), pp. 74–98.
- <sup>57</sup>Such as at the University of Washington, Seattle, and San Diego State University. See, L. C. McDermott, "A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers," *Am. J. Phys.* **58**(8), 734–742 (1990).
- <sup>58</sup>Such as found in J. Minstrell, "Teaching science for understanding," in *Toward the Thinking Curriculum: Current Cognitive Research*, edited by L. Resnick and L. Klopfer (ASCD, Alexandria, VA, 1989), pp. 129–149; W.-M. Roth and A. Roychoudhury, "The development of science process skills in authentic contexts," *J. Res. Sci. Teach.* **30**(2), 127–152 (1993); and in Refs. 12, 13, and 34.
- <sup>59</sup>Bruner, 1986, cited in Ref. 10; J. H. Shulman, *Case Methods in Teacher Education* (Teachers College Press, New York, 1992); D. Shifter, *What's Happening in Math Class; Issues of Practice in Teacher Narratives from the Mathematics Education Reform Movement*. (Teachers College Press, New York, 1995).

## WRITING REVIEW ARTICLES

Unfortunately, that information explosion is in great part a misinformation explosion. All of us are exposed to huge amounts of material, consisting of data, ideas, and conclusions—much of it wrong or misunderstood or just plain confused. There is a crying need for more intelligent commentary and review.

We must attach a higher prestige to that very creative act, the writing of serious review articles and books that distinguish the reliable from the unreliable and systematize and encapsulate, in the form of reasonably successful theories and other schemata, what does seem reliable. If an academic publishes a novel research result at the frontier of knowledge in science or scholarship, he or she may reap a reward in the form of a professorship or a promotion, even if the result is later shown to be entirely wrong. However, clarifying the meaning of what has already been done (or picking out what is worth learning from what is not) is much less likely to advance an academic career. Humanity will be much better off when the reward structure is altered so that selection pressures on careers favor the sorting out of information as well as its acquisition.

Murray Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex* (W. H. Freeman and Company, New York, 1994), pp. 342–343.