# Student resources for learning introductory physics

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(Received 26 January 2000; accepted 5 April 2000)

With good reason, physics education research has focused almost exclusively on student difficulties and misconceptions. This work has been productive for curriculum development as well as in motivating the physics teaching community to examine and reconsider methods and assumptions, but it is limited in what it can tell us about student knowledge and learning. This article reviews perspectives on student resources for learning, with an emphasis on the practical benefits to be gained for instruction.

## I. INTRODUCTION

By and large, physics education research has been dominated by studies of student misconceptions and difficulties. The former are more specifically defined as stable cognitive structures; the latter notion is theoretically noncommittal, but both are concerned with understanding aspects of students' knowledge and reasoning that present obstacles to learning.

Without question, this work has been and continues to be productive, for curriculum development as well as for motivating the physics teaching community to examine and reconsider conventional methods of instruction. Nevertheless, as views of student knowledge and reasoning, misconceptions and difficulties are limited in two important respects. First, they provide no account of productive resources students have for advancing in their understanding. Second, descriptions of student difficulties provide no analysis of underlying mechanism, while the perspective of misconceptions cannot explain the contextual sensitivities of student reasoning,[1,2] such as the empirical fact that substantively equivalent questions, posed in different ways, can evoke different responses from the same student.[3]

My purpose in this article is to review current ideas for thinking about students in terms of the resources they bring to learning. In this description I will emphasize how these resources can be productive, but this view of resources is not complementary to that of difficulties. Rather, an account of student resources should provide theoretical underpinnings to understanding difficulties as well.

I begin with a rough description of the general notion of a resource. Then I discuss ''conceptual resources'' students bring to understanding physical phenomena and concepts, emphasizing how an understanding of these resources may be of direct, practical benefit for instruction. I then present some initial ideas about ''epistemological resources'' students have for understanding knowledge and learning, again emphasizing instructional utility.

### A. The rough idea

Presented with a sufficiently unfamiliar problem, physicists generally begin by searching their knowledge and experience, trying out different ways of thinking.[4]

As an example, consider the following:

> Suppose you place a box in a stream of water, and suppose the temperature of the water is 20 °C. If the temperature of the box is less than 20 °C, then the effect of water flowing over the box will be to raise its temperature; if the temperature of the box is greater than 20 °C, then the effect of the water flowing will be to reduce its temperature. Of course, there may be other factors as well: The box may have an internal source of energy; it may be in thermal contact with the air or with the ground, either of which could have a different temperature. Still, if the box is warmer than 20 °C, the water cools it, and if the box is cooler than 20 °C, the water warms it.
>
> Now suppose you place the box in a ''stream'' of sunlight. What is the corresponding temperature of the box, if there is one, such that if the box is cooler than that temperature the effect of the sunlight is to warm it, and, if the box is warmer than that temperature, the effect of the sunlight is to cool it (more rapidly, that is, than the box would cool in the absence of sunlight)?

If you have not seen this question before it may be useful to pause and work on it a little before reading on, to conduct an informal case-study of your own reasoning.

The question invites you to compare a stream of sunlight to a stream of water. Applying that analogy brings the idea that the ''break-even'' temperature is the temperature of the sunlight. Readers of this journal have a variety of relevant resources. Perhaps you know this temperature offhand; perhaps you will apply your knowledge of blackbody spectra and your knowledge that the light from the sun looks yellow.

But there are other ways you could think about the problem. Rather than think of the sunlight as a material flowing over and past the box (like water), you may think of it as a form of energy the box absorbs. Among the resources you would apply in this way of thinking is one for understanding an accumulation, in this case an accumulation of energy in the box. If you apply this way of thinking, you may conclude that the incident sunlight can only add to the energy of the box, and thus the effect of the sunlight would always be to increase the temperature of the box (or to decrease the rate of cooling).

Both of these ways of thinking consider the *sunlight* acting on the *box*. Of course, the box can emit light as well as absorb it; like the sun the box's emissions depend on its temperature. Thinking of an equilibrium between absorption and emission of light makes it difficult to think of the stream of sunlight as analogous to the stream of water, as the question suggested. It may be useful to stop thinking about the sunlight as the other object in the interaction, and to think of the sun as the other object, that is to think of the sun and the box as acting on each other, through light.

What I am describing are a variety of ways of thinking about the question. If you paused to think about the problem, it is not unlikely you came up with some I have not mentioned. The important point here is that, as a physicist, you have developed a range of resources for thinking about physical situations. Given a familiar problem, you already know which of these resources to apply, and you do so efficiently. Given an unfamiliar problem, you need to search through your resources, perhaps trying several of them out before you arrive at those you find to be useful. Often, as may happen with this problem, you have active at the same time multiple ways of thinking about a problem that conflict with each other, and much of the work you need to do is to reconcile that conflict. Here, the ‘‘sunlight can only add energy’’ reasoning conflicts with the ‘‘thermal equilibrium’’ reasoning; reconciling that conflict entails finding a flaw in one or the other line of reasoning.

Sometimes you make a mistake in applying a resource, by supposing it is useful for solving a problem in a way that it turns out not to be. But that does not mean the resource itself is invalid, as this problem illustrates. The notion of equilibrium, for example, is a powerful and important resource, but it does not turn out to be useful for thinking about the box in sunlight in the way it is for thinking about the box in water. To apply that resource, it would be necessary to think of the box as in constant thermal contact with the *electromagnetic field*, but their interaction is very far from equilibrium.

### B. A computational metaphor

This use of the word ‘‘resource’’ derives loosely from the notion of a resource in computer science, a chunk of computer code that can be incorporated into programs to perform some function. Programmers virtually never write their programs from scratch. Rather, they draw on a rich store of routines and subroutines, procedures of various sizes and functions. Depending on their specialization, different computer programmers would have assembled for themselves different sets of procedures. Those who specialize in graphics have procedures for translating and rotating images, for example, which they use and reuse in a variety of circumstances. And, often, a programmer will try to use a procedure in a way that turns out to be ineffective.

This metaphor of the mind as a computer—and certainly for some it is more than a metaphor—has been developed explicitly by researchers in artificial intelligence. The essential point here is that mental phenomena are attributed to the action of many ‘‘agents’’[5] acting in parallel, sometimes coherently and sometimes not, rather than as resulting from the action or properties of a single entity. Thinking about the sunlight problem, for example, activates many resources at once; much of the challenge is to bring these activations into coherence. This differs from the notion of a ‘‘misconception,’’ according to which a student's incorrect reasoning results from a single cognitive unit, namely the ‘‘conception,’’ which is either consistent or inconsistent with expert understanding.

## II. CONCEPTUAL RESOURCES

Most instructors have at least a tacit sense of student resources. In fact, much of naive instructional practice is characterized by inappropriate presumptions regarding the resources students have available. The emphasis in the physics education research literature on difficulties and misconceptions is largely by design, to address and debunk these presumptions. It is now abundantly clear that students do not have well-formed, prerequisite conceptions, such as of ‘‘mass,’’ ‘‘air,’’ ‘‘force,’’ and ‘‘velocity,’’ as instructors often unknowingly assume. Nor, as it has become trite to admonish, are students ‘‘blank slates’’ on which instructors can inscribe correct ideas. To the contrary, students have a great deal of knowledge about the physical world formed from their everyday experience, and physics instructors are prone to underestimate the extent to which that knowledge differs, in substance and structure, from what they hope to impart.

However, that students lack productive resources in the form naive instructors presume does not mean that they lack productive resources entirely. There is broad consensus among physics education researchers that students ‘‘construct’’ new knowledge from prior knowledge; this obviously implies that students have in their prior knowledge the raw material for that construction. Nevertheless, in its emphasis on difficulties and misconceptions, physics education research has mostly overlooked the task of studying and describing this raw material.

It is to the interest both of progressing toward a theory of physics learning and of designing and implementing effective instruction that physics education researchers come to understand the resources students bring to learning introductory physics. Because effective instructors already have a rich, tacit sense of these resources, there is much to be gained from mining for insights embedded in their practices. In this section, I will discuss some instructional practices that are tied to insights into student conceptual resources.

### A. Anchoring conceptions and bridging analogies

Clement, Brown, and Zeitsman[6] highlighted the existence of productive resources in students' understanding, noting that ‘‘not all preconceptions are misconceptions.’’ They described ‘‘anchoring conceptions’’ in which student understanding typically aligns well with physicists' and how these may serve as targets of ‘‘bridging analogies’’ to help students apply that understanding in other contexts.

Minstrell's[7] strategy for helping students understand the Newtonian idea of a passive force, such as the force exerted upward by a table on a book, is a touchstone example. Students generally have difficulty with the idea that the table can exert a force. Asked, for example, to draw a free-body diagram for the book, students often draw a downward gravitational force but omit the upward contact force exerted by the table. Many explicitly contend that a table cannot exert a force, but, rather, ‘‘gets in the way’’ or ‘‘blocks’’ the book from falling. In other words, students have difficulty understanding the table as having a causal role in the interaction, because the table seems to be an inherently passive object: How can a table ‘‘exert’’?

Students do not, however, typically have that difficulty when thinking about a spring. They readily see a compressed spring as ‘‘exerting’’ force against its compression. They can ‘‘see’’ it pushing. Minstrell's[7] strategy uses students' understanding of springs as a productive resource, the anchoring conception[6] from which to build an understanding of passive forces. Specifically, he uses a series of bridging analogies[6] to help students learn to see a table as an extremely stiff spring.

In sum, students have resources for thinking about springs that, if activated, are productive for their developing a Newtonian understanding of passive forces. An instructor such as Minstrell who is aware of these resources can design instruction to help bring about that activation.

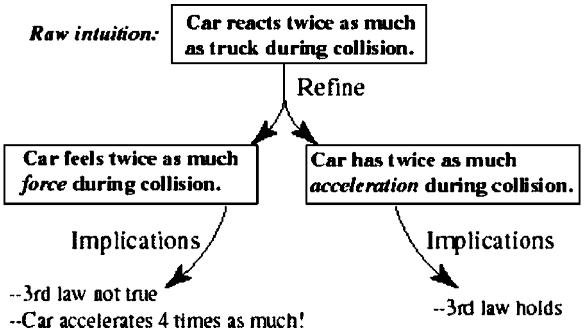

Fig. 1. From Elby (in preparation).

### B. Refining ‘‘raw intuitions’’

Elby[8] describes another instructional strategy that illustrates a resources-based view of student knowledge. The context for this example is a lesson on Newton's third law. As part of the lesson, Elby posed to students the following question:

> A truck rams into a parked car, which has half the mass of the truck. 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?

That most students responded that the truck exerts a larger force on the car than the car exerts on the truck is not surprising; this is a commonly recognized misconception. Elby then posed them another question:

> Suppose the truck has mass 1000 kg and the car has mass 500 kg. 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.

This time, most of the students answered correctly; and by working through follow-up questions, they came to the conclusion that their ‘‘instincts’’ agree with Newton's third law. Elby identified students' correct answer to this question as reflecting their ‘‘raw intuition’’ that ‘‘the car reacts twice as much during the collision,’’ and he lead them to the idea that they could ‘‘refine’’ this ‘‘everyday thinking’’[9] in one of (at least) two ways. Figure 1 depicts the diagram Elby drew on the blackboard during this discussion to show the two options for refining the raw intuition and the implications of each refinement.

Elby identified the notion that ‘‘the car reacts twice as much’’ as a resource from which students could build their understanding. Depending on how they used this resource, how, in Elby's terms, they refined it, the idea could contribute to a Newtonian understanding or it could pose a difficulty for that understanding. In this way, what Elby loosely characterized as a raw intuition provided the raw material for students in building their understanding. Like a subroutine for a programmer, the intuition itself is neither correct nor incorrect; it becomes correct or incorrect in its use.

What this meant in class for Elby was an instructional strategy explicitly designed to help students refine their intuition toward a coherent understanding. He guided them to see the consequences of the two alternatives. If they apply their ‘‘car reacts twice as much’’ intuition to the concept of force, their reasoning leads to a contradiction with Newton's third law. If they apply it to the concept of acceleration, their reasoning is consistent with Newton's laws.

In this way, a resources-based account of student knowledge and reasoning does not disregard difficulties or phenomena associated with misconceptions. Rather, on this view, a difficulty represents a tendency to misapply resources, and misconceptions represent robust patterns of misapplication.

A similar view of student knowledge motivated Minstrell to coin the term ‘‘facet.’’ Elby's raw intuition here would constitute a facet of student understanding that students could apply productively or counter-productively. Understanding the students in this way, the task for instruction becomes helping students ‘‘unravel’’ and ‘‘reweave’’ the strands of their knowledge and understanding, in Minstrell's metaphor,[10] rather than removing or replacing conceptions.

### C. Toward a more precise model of conceptual resources

These are not technical terms: Minstrell and Elby chose ‘‘facet’’ and ‘‘raw intuition’’ largely for pedagogical and practical reasons, to make the general notion accessible to a broad audience, including secondary students. This general level of description is useful, but developing a model of physics knowledge and learning will eventually require more precise ideas and terminology.

DiSessa[11] has pursued a technically more precise model, beginning with his account of ‘‘phenomenological primitives,’’ or ‘‘*p*-prims,’’ as one form of cognitive structure. To return for a moment to the computational metaphor, a programmer writes routines from subroutines, and subroutines from smaller subroutines, and so on. At the lowest level of this progression are the ‘‘primitives’’ of the given computer language (e.g., FORTRAN), the smallest units of code. Similarly, a ‘‘primitive’’ resource would be the smallest chunk of cognitive structure. DiSessa[11] conjectures *p*-prims as one form of primitive cognitive structure.

For example, asked to explain why it is hotter in the summer than in the winter, many students will respond that it is because the earth is closer to the sun.[12] The usual interpretation attributes this response to a faulty conception students have formed, by which the earth moves in a highly eccentric ellipse around the sun, and in some cases this may be the student's view. An alternative interpretation, however, is that some students do not have this previous conception regarding the cause of the seasons but generate it on the spot. Asked the question, they conduct a quick search in their knowledge and reasoning for a way to think about it. One of the first resources they identify is the general notion that getting closer to a source increases the intensity of its effect: *Closer means stronger*.

As a primitive, *closer means stronger* is a resource productively activated to understand a number of phenomena: The light is more intense closer to the bulb; music is louder closer to the speaker; an odor is more intense closer to its source. Students' tendency to explain seasons in terms of proximity to the sun may be seen as a faulty activation of this resource, rather than as reflecting a faulty, previously existing conception.

DiSessa's[11] account affords a more fine-grained analysis of Clement and Minstrell's bridging analogy. The situation of the book on the table tends to activate a primitive *blocking*: The table blocks the book from falling. As a primitive element of student reasoning, *blocking* needs no explanation, and its activation in this context represents a difficulty. Meanwhile, springs tend to activate *springiness*, a primitive notion of a restoring agency acting in response to a deformation. The bridging analogy helps to activate *springiness* to the situation of the book on the table; that activation can be reinforced by a demonstration to show the table's deformation.[7] *Springiness* would cue other primitives as well, including *maintaining agency*, by which the students understand the deformation of the table as causing and maintaining an upward force on the book, and *balancing* by which students see an equilibrium between the weight of the book downward and the upward force by the table. It is also important that these activations would tend to deactivate *blocking*, and students arrive at a new understanding of the book on the table. (The account predicts that as they become robust in their new understanding, students should have difficulty remembering what it was they had been thinking earlier. With *blocking* deactivated, they would not have access to the sense it had provided of the situation.)

In sum, on diSessa's view, the function of an anchoring conception is to activate productive resources, and the function of a bridging analogy is to carry those activations back to the problem at hand. Of course, this account of the activation of primitives is conjectural. I present it to illustrate the possibilities in a resource-based account. Brown[13] discussed this role of analogies as ''refocusing core intuitions,'' using *p*-prims as a model of a core intuition. In principle, this model of primitives' activations could be developed and tested computationally, with the *p*-prims at the nodes of a connectionist system.*

Similarly, one could depict the raw intuition in Elby's example as a set of primitives. The different posings of the question activate the same set of primitives but apply them differently. The details of that account are not important here, and they would again be conjectural, so I leave them as an exercise to the reader.

### D. Instructional design

Elby's[8] example illustrates an advantage for instruction of having insight into student resources: Instruction can be designed to help students use their resources more productively. Here I discuss two other examples to illustrate how that design may be sensitive to details of the model of student thinking.

Wittmann's[14] analysis of student reasoning about waves suggests that many of their difficulties arise from their misapplying resources for thinking about objects. Their behavior fits diSessa and Sherin's[15] account of *object* as a ''coordination class,'' another form of cognitive structure, a coherent set of associations and strategies. DiSessa and Sherrin developed this structure to improve our technical precision for thinking about what may constitute one form of ''concept.'' The coordination class of *object*, for example, consists of particular expectations and strategies for reasoning and obtaining information. That is, to think about *X* as an *object* is to expect it to have properties of form, location, permanence, mass (in an intuitive sense), and velocity; and it is to expect that one can find out about *X* through various strategies, such as by looking for it (if it is within sight), touching it (if within reach), hefting it, and so on.

That resource, however, is not productively applied to waves, and a number of difficulties arise. Students expect, for example, that the impact of a sound wave will propel a dust particle across the room, or that ''flicking your hand harder'' will cause a wave pulse to move more quickly down a string. The insight that these difficulties originate in students thinking of waves as *objects* is useful in designing a tutorial. Exercises in the tutorial can specifically highlight differences between the behavior of waves and the behavior of *objects*, to help students stop thinking in this way.

Still, this insight raises the question: What resources do students have in their prior knowledge that are productive for thinking about waves? Staying within diSessa and Sherin's framework, if student difficulties arise from their coordinating their expectations and strategies by the class of *object*, what other coordination class would be a productive starting point from which to develop a physicist's understanding?

One possible answer, worth exploration, is the coordination class of ''event.'' To think about *X* as an *event*[16] is to expect it to have a location, a time of occurrence, a duration, and a cause; and it is to expect that one can find about *X* by looking for it (at the moment it is occurring). But one does not think of touching or hefting an *event*, which are strategies appropriate for *objects*. This may be a productive coordination class to bring to bear on reasoning about waves, and if so it would be useful to design a tutorial to help students think of waves as *events* rather than *objects*. Thus a tutorial might include a comparison to a series of dominoes toppling, a succession of *events*, one causing the next, propagating through space.

Rosenberg[17] provides another example, similar to Wittmann's, of a difficulty arising from the application of an otherwise useful resource. Rosenberg speaks of a ''principle of exclusivity'' as a generally useful resource for thinking about values: A quantity can hold only one value at any time. This resource is applicable, for example, for constructing an understanding of the mathematical concept of a function. An object can be in only one location at a time; thus its location can be written as a function of time. Student difficulties in quantum mechanics, Rosenberg conjectures, arise in part from their applying the principle of exclusivity to their thinking about values, including location, for quantum objects such as electrons.

Here is an example in which a more precise understanding of the nature of the resource could have dramatic implications for instruction.[18] If, for example, this resource is a *p*-prim, then its activation is highly sensitive to context, and it should be possible to deactivate through manipulations of contexts, such as through bridging analogies or confrontation. Another possibility is that this resource, when it is fully described, will be another form of cognitive structure, more distributed and constitutional than a *p*-prim (more like a property of the operating system than like a chunk of code), and if this is the case, ''deactivation'' may not be an option.

### E. Instructors' tacit knowledge

Of course, teachers and curriculum developers are guided by their sense of what students know that may contribute to their learning. As a prominent example, Hewitt's text[19] is rich in common sense explanations of physics concepts. Embedded in these explanations are insights into what students know that may be productively applied to their learning. For example, his strategy of writing equations with exaggerated or diminished symbols, such as in Fig. 2, is motivated by a

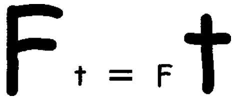

Fig. 2. Hewitt-style depiction of how the impulse of a large force over a small time can equal that of a small force over a large time.

sense of students' productive intuitions for balancing. There are many examples to be found in other current instructional texts as well.[20–22]

Nevertheless, whereas the physics education research community has devoted substantial attention to studying the nature of student difficulties, it has paid little attention to documenting and systematizing extant ideas about student resources. Without that attention, this knowledge remains mostly tacit and unexamined. I am arguing that it should become a primary agenda of the physics education research community to develop explicit accounts of student resources, to allow their exchange, review, and refinement.

If, for example, students' intuitive sense of balancing is well described as a primitive in diSessa's framework, then its activation may be temporary for many students reading Hewitt's textbook: The figure may be effective at cueing the primitive, and students will have a sense of understanding. Later, in another context, the primitive may no longer be activated and students would no longer have access to the sense they experienced looking at the figure. How instructors appeal to student resources, and what they expect will result, depends critically on how they understand the nature of those resources.

This is relevant not only to curriculum development but also to how teachers interact with students in specific moments of learning and instruction. In earlier work,[1,23] I compared the perspectives of misconceptions and *p*-prims with respect to how they may influence what an instructor perceives in student knowledge and reasoning. Instructors who expect productive resources will be inclined to look for those resources in their students' reasoning, engaging them in ways that are not limited to confrontation,[24] and, like Minstrell, Elby, and Hewitt, helping students find and build from those resources. Again, it is essential to articulate, examine, and refine the instructors' sense of student resources, because the details of this understanding may have significant consequences in how instructors attend and respond to student thinking.

## III. EPISTEMOLOGICAL RESOURCES

Physics education research has traditionally focused on student conceptual understanding. In recent years, however, some researchers have paid significant attention to student epistemologies—their understanding of the nature of knowledge and how it is obtained. Three different instruments[25–27] have been developed to assess what students believe about knowledge and learning in introductory physics. Some physics students, for example, may believe learning consists of memorizing facts and formulas provided by the teacher, while others may believe it entails applying and modifying their own understandings.[28] For teachers, awareness of these beliefs provides an alternate perspective into students' behavior.[29] Rather than see students as lacking in common sense, e.g., a teacher could see them as believing common sense is irrelevant to learning physics.

The study of epistemologies has generally emulated the study of conceptual understanding in presuming essentially unitary structures, ''beliefs,'' as components of essentially stable epistemologies.[30] Construed in this way, epistemological beliefs are analogous to the concepts posited as elements of cognitive structure, and research on epistemologies has mostly focused on students' ''misbeliefs'' about physics and physics learning (e.g., that learning consists of memorizing) that differ from expert beliefs. Like misconceptions, these misbeliefs could not be understood to contribute to productive epistemologies.

We[30] are beginning to develop an account of context-dependent epistemological resources, at a finer grain-size than ''beliefs.'' Like conceptual resources, these epistemological resources are activated in some contexts but not others, and are productive in some contexts but not others. For example, many students appear to view scientific knowledge as coming from authority. At the same time, it is clear 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?'' ''Because I saw you hide something under your coat!'').

To appreciate the role of these resources in physics reasoning, consider again the question of the box in the sunlight. Discussing it above, I focused on various sorts of conceptual resources physicists might apply. But that reasoning involves other sorts of resources as well, including some developed for the tasks of managing the conceptual resources.

These resources might entail a sense of knowledge as connected and constructable (and reconstructable): You expect that the answer to this question can be constructed using knowledge you already have in place. In other contexts, such as answering the question ''What is the capital of Lithuania?,'' you may do better to activate resources for thinking of knowledge as factual and communicable. That is, rather than choose to search within your own knowledge and experience you would choose to search for that information from documents or from experts.

Having chosen to conduct a search within your own knowledge and experience, you have further resources for evaluating the results of that search. You know, for example, not necessarily to trust the first idea you find; you know to compare different ways of thinking with each other; you know to monitor for coherence in your understanding and to address inconsistencies when you find them. For example, you may have quickly decided that the sunlight can only add energy to the box, and from there spent most of your time trying to identify specifically why it does not work to reason in terms of equilibrium. In other contexts, such as in deciding what to have for dinner, once you decide on an answer you would stop thinking about the question. It would be odd to spend time trying to identify specifically what would be wrong with choosing lasagna, e.g., once you had chosen grilled salmon. For some students, the two situations may activate the same epistemological resources, and they may consider it odd to continue thinking about a physics problem once they have chosen an answer.

Part of learning physics thus involves learning when to activate which epistemological resources. To help with this, instructors need understanding of these resources, but there has been very little research on the subject. In developing our account, we are drawing insights from Minsky,[5] whose agents include a number concerned with epistemology, as well as from Collins and Ferguson,[31] who described various ‘‘epistemic forms’’ (e.g., lists, stories, rules) and ‘‘epistemic games’’ (e.g., listing, categorizing, guessing) as everyday epistemological resources.

We are also, as I suggested above, mining for insights embedded in instructional practices. Reasoning in terms of students’ epistemological resources provides a new interpretation of existing strategies and may guide the implementation and refinement of those strategies. Here I sketch several examples of relevant instructional practices.

### A. Modifying the instructional context

On this view of student epistemologies, difficulties generally attributed to stable beliefs may also be understood in terms of counter-productive resource activations. Rather than think in terms of confronting misbeliefs, an instructor could think in terms of modifying the resources students activate. A core difference between conventional and reformed physics instruction may be in the epistemological resources the different instructional contexts tend to activate.

Encouraging debates in science class for example, certainly not a new practice, may be understood as a means of helping students activate a set of epistemological resources they have available for understanding argumentation and differing points-of-view. The class may become a context in which students understand it as important to explore a variety of perspectives, as opposed to looking for the ‘‘one right way’’ of thinking about the issue at hand. These are resources they activate (or should!) in the contexts of debates about, e.g., politics and history, and they may be productively activated in physics as well.

Much of the benefit of innovative pedagogical approaches can be understood in these terms. They change the context in such a way as to invoke productive epistemological resources. Another example is engaging students in activities of design and construction, such as building gadgets or writing computer programs that accomplish some task. Students have resources for understanding these sorts of activities, of what it means to make something, try it, and adjust it to improve performance.[32] That understanding may also be used to activate resources productive for learning.

Hestenes and his colleagues design instruction around the core notion of modeling and ‘‘modeling games,’’[33] an approach that may be understood in terms of activating epistemological resources for understanding physics knowledge and reasoning in terms of the formation and application of models, rather than in terms of facts and procedures for solving problems. Similar resources may be promoted by instruction designed around the core activity of computer programming. The task, for example, of writing a computer program to model a Newtonian object, should activate epistemological resources for understanding knowledge as constructed, represented formally (as a program), and as an approximation of reality.[34]

### B. Epistemological anchors

The general notion of epistemological resources suggests the strategy of looking for ‘‘epistemological anchors’’ in students’ understandings of familiar situations and activities, an epistemological version of Clement, Brown, and Zeitsman’s[6] notion of anchoring conceptions. Again, rather than understand student epistemologies only in terms of counterproductive misbeliefs to be exposed and confronted, a teacher may understand students as having productive epistemological resources they naturally invoke in other contexts. These anchors may serve as targets for epistemological metaphors or bridging analogies.

For a familiar example, many instructors compare mental exertion to physical exertion, to help students think of knowledge and ability as developed through effort. In that case, the context of physical exercise serves as the epistemological anchor, a context in which students naturally associate effort and persistence with improvement.

Elby’s ‘‘refining raw intuition’’ lesson[8] provides another example. Elby developed his strategy specifically toward an epistemological agenda of helping his students to understand learning as ‘‘the refinement of everyday thinking.’’[9] This, again, is a means of activating a different set of epistemological resources than students would typically invoke in physics, to help them think in terms of modifying what they already know rather than solely in terms of receiving new information. By casting the activity of learning as the ‘‘refinement’’ of ‘‘raw intuition,’’ Elby was essentially invoking a metaphor for learning physics as the refinement of preexisting material, as opposed to a replacement of ‘‘bad’’ material by ‘‘good’’ material.

The following is another example, drawn from a discussion in an introductory physics course. It is a bridging analogy to interpersonal relationships, designed to get physics students to reflect about their own thought processes.

> ‘‘Imagine you have met a new person and he irritates you for some reason you can’t put your finger on. So you think about it, trying to figure out what it is about him that bugs you, and eventually you realize that it’s because 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 irritates you, but that movie character, and you don’t have to worry about it any more. In another instance, you may realize that you’ve met him before and had an unpleasant interaction, in which case there’s good reason for that feeling of irritation.
>
> 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.’’

In this case, the everyday reasoning activity of trying to figure out why a new person seems familiar serves as an epistemological anchor to help students understand the phenomenon of having a physical intuition, to motivate a similar introspection to find its source.

Other targets of epistemological analogies could include the activity of figuring out the best way to arrange the furniture in the living room, to activate resources for thinking of ideas as logically connected (‘‘If I put the couch on the east wall, the bookcase won’t fit anywhere but next to the window''), and the activity of giving directions to a traveler, to help activate resources for understanding the importance of precision.

## IV. CLOSING THOUGHTS: THE BENEFITS OF ''MESSING ABOUT''

To date, and with good reasons, physics education research has focused almost exclusively on student difficulties and misconceptions. I have written this article to help motivate a shift toward the study of resources, toward better comprehension of (1) the *productive* aspects of student knowledge and reasoning, the raw material from which they may construct a physicist's understanding, and (2) the underlying dynamics of the difficulties and misconceptions students often have in that construction.

At this point, there are only early ideas for how to understand and model these resources, and to determine what forms they may take in the minds of students (and of physicists). Still, I hope to have illustrated that even these early ideas can be useful in instruction and that there are clear benefits to be gained from more refined understanding. With respect to conceptual resources, there are promising directions for that refinement. Physics education research needs to begin to make progress with respect to other resources as well, including epistemological resources.

Discussing the instructional relevance of developing a view of student resources, I have focused in this article on the advantages of having a sense of the resources students have in place: Instructors who expect productive resources will be inclined to look for them in their students' reasoning, and, as important, to help students look for them themselves. These strategies presume that students' resources are mostly in place, a presumption that is probably generally valid for older students, although there may be some important exceptions.

Clearly this general view of resources also requires an account of how students, mostly as children, construct these resources in the first place. This topic, of course, has long been the domain of research on cognitive development in early childhood, wherein scholars have often advocated approaches to instruction along the lines of what David Hawkins famously called ''messing about in science.''[35] A resources-based view of student knowledge and reasoning would support their arguments.

In particular, such a view suggests two distinct needs for the development of a scientific understanding: (1) the formation of intellectual resources and (2) the (re)organization and application of these resources to align with scientific knowledge and practices. On the view I have summarized in this article, high school and college students learning introductory physics should mostly be seen as addressing the second need. It is possible that early science education should mostly be seen as addressing the first. That is, in whatever form they may appear, children must develop resources, such as *closer means stronger* or *springiness* or the raw intuition Elby described, before they can refine their application toward a physicist's understanding.

Moreover, children mostly form these resources *prior to their correct alignment with physics concepts*. It is at least possible that this priority is necessary. In other words, a resources-based view of knowledge suggests that students are not ready to understand a concept until they have developed resources from which to construct it. Of course, many of these conceptual resources, including *closer means stronger* and *springiness*, are likely to develop in early childhood independent of schooling. Other resources, such as the notion of equilibrium, may not develop fully prior to schooling. Perhaps more at risk, however, are the epistemological resources necessary for finding, applying, and modifying these conceptual resources.

For example, visiting an elementary class recently, I showed a standard demonstration in which I sprinkled black pepper over a pan of water and then touched the surface with a toothpick I had dipped in soap. The students saw the pepper recede quickly from where I had touched, and I asked them to write out their explanations of what was happening. Some of the students thought of the phenomenon in terms of the soap pushing the pepper away, describing the soap as expanding and ''taking up space.'' Others knew it had something to do with ''surface tension''—they had earlier seen phenomena with soap and surface tension—but they could not be more specific. Of course, the latter were more correct: The soap weakens the surface tension, and the pepper is *pulled* by the un-soapy water surrounding where I touched. But I contend that the former students were closer to scientific thinking, because their explanation was comprised of a tangible mechanism rather than a phrase they did not understand.

Here, then, is a reason for students' early education in science to consist largely (and perhaps primarily) of ''messing about:''[35] It is in this way they can best develop the resources they will need later. Messing about, in hands-on activities or in playful, student-controlled conversations,[36] may be more productive than experiences crafted to guide students toward correct understandings of the concepts.

In fact, efforts to promote students' correct understanding at this early stage, and in particular their correct use of terminology, may be counter-productive, impeding children's construction and application of productive resources. One common liability is that they come to see science learning in terms of remembering ''magic words''[37] rather than, e.g., of applying and developing their sense of mechanism. That students typically arrive at introductory physics with counter-productive beliefs and expectations about physics and physics instruction[26] can be directly traced to their prior experiences in science instruction.

A piece of this argument deserves particular emphasis: For students new to scientific thinking, ''wrong'' thinking should be seen as productive if it helps develop resources for later ''right'' thinking. To be sure, there have been many examples in the history of science of resources having been developed, failing in their original purpose, but proving to be productive later when used in other ways. It was Aristotle who first argued that an object cannot exert a force on itself; the Lorentz transformations were first developed for the ether theory; mathematical tools for understanding knots, developed in the 1800s as an early and unsuccessful particle theory, are now useful in nonlinear dynamics.[38] By analogy, students may develop productive resources through ''wrong'' thinking, especially in early grades. Children who argue that objects sink or float depending on their weight are incorrect, but in that incorrect thinking they may be applying and developing resources they will be able to use in different ways later.

This is certainly not to suggest that ''messing about'' is the entirety of science learning; it is to suggest that messing about may play an essential early role, and that educators ignore this role at their students' peril. Learning science cannot end with ''messing about,'' but it may need to begin there, just as learning to draw must begin with scribbling. To insist from the beginning that children's drawings be ''correct'' (bear a good resemblance to what they say they are drawing) would be to prevent them from learning to draw. For similar reasons, science education may need not only to tolerate but to encourage the equivalent of scribbling in early learning.

## ACKNOWLEDGMENTS

I am grateful to Andy Elby, Joe Redish, and two anonymous reviewers for numerous comments and suggestions, both substantive and editorial.

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