

LEARNING AND INSTRUCTION IN PRE-COLLEGE PHYSICAL SCIENCE

Traditional teaching practices only poorly reflect what is known about the learning process. To improve science education, teachers and scientists must take note of the implications of cognitive science.

Jose P. Mestre

THE FAR SIDE

By GARY LARSON



"Mr. Osborne, may I be excused? My brain is full."

Two main instructional practices are found in American education: One is prevalent, while the other is emerging. We have all experienced the prevalent practice, which results from the so-called transmission model of instruction. In this model, students are exposed to content through lectures, presentations and readings, and are expected to absorb the transmitted knowledge in ready-to-use form. Although it is not a model of learning *per se*, the transmission model does make a pivotal assumption about learning, namely that the message the student receives is the message the teacher intended. Within this model, students' difficulties in grasping a concept are interpreted as indications that the presentation was not clear or forceful enough to be understood (that is, the signal being transmitted was either weak or garbled). Thus many users of the transmission model believe that if they make the presentation more lucid or persistent—for example, by transmitting at a slower speed or in a louder voice—students will eventually understand. Too often we are inclined to believe that by speaking in shorter words and

sentences we can teach the big ideas in relativity to ninth-graders; this is simply not the case if the students' intellectual development is not at a level where they can appreciate the subtleties of difficult concepts.

The transmission model is used largely by default rather than choice, both because it is the instructional method by which we were taught and because it may be the only instructional method we know. Not only does it have little theoretical justification, but there is mounting evidence that it is not the most efficient method of instruction.

Unlike the transmission model, the second major instructional practice, which has emerged over the last decade, begins with what is commonly termed the constructivist model of learning, constructivist epistemology, or simply constructivism.¹⁻⁵ This model contends that all of our knowledge is the result of our having constructed it. The construction of knowledge is a lifelong, effortful process. At any time, the corpus of knowledge we have constructed makes sense to us and helps us interpret

or predict events in our experiential world. Meaningful learning, in the sense that we are able to interpret and apply knowledge in novel contexts, requires significant mental engagement by the learner.

This view of learning is antithetical to the view tacitly assumed in the transmission model. More specifically, constructivism contends that students are not sponges ready to absorb and use transmitted knowledge; the knowledge already written on their mental slates affects how they interpret new observations and how they accommodate newly acquired knowledge. If during the course of instruction we do not take cognizance of students' prior knowledge, it is likely that the message transmitted will not be the message received.

The box on page 58 gives a possible classroom dialogue between a teacher and several students that employs a constructivist approach. Note that the teacher plays the role of facilitator rather than transmitter of knowledge; the teacher probes the students' understanding and helps them resolve conflicts between scientific concepts and their prior knowledge. This example also illustrates that constructivism does not advocate that students "discover" everything for themselves. Rather, constructivist instruction focuses on relating new knowledge both to previously learned knowledge and to experiential phenomena so that students can build a consistent picture of the physical world.

Students' misconceptions

Evidence from the research literature supports the constructivist view of learning. The scientific knowledge students possess is incomplete, fragmented, and often fraught with "naïve theories" or misconceptions that are inconsistent with scientific concepts.⁴⁻⁷ (See Lillian C. McDermott's article in *PHYSICS TODAY*, July 1984, page 24.) Figure 1 provides a sampling of common misconceptions.

Unfortunately, because students have spent considerable mental effort constructing their "theories," and because these theories do explain and predict some subset of physical phenomena, students do not relinquish their misconceptions easily in favor of scientific concepts. Research consistently shows that students embrace their erroneous beliefs tenaciously and often explain away observations or events that, from the perspective of a scientist, directly conflict with their naïve theories. This occurs because students either view events through the myopic eye of the naïve theory or make inconsequential modifications to their theories in ways that fail to resolve the contradictions.^{5,8}

Perhaps the most convincing evidence that misconceptions are deep rooted and difficult to dislodge with traditional instruction is that many persist even after students complete, and receive high grades in, science

courses taught by competent instructors. Students completing such courses can usually perform complex calculations and solve the problems required to achieve a high grade, but are incapable of displaying an understanding of the concepts underlying the problems' solutions.^{3,5,7}

Fortunately, in any given topic a very small number of misconceptions account for most of the confusion, so that identifying and dealing with them during the course of instruction is a manageable task. Although there are no tried-and-true methods for helping students overcome misconceptions, some approaches based on the constructivist view have been shown to be effective.⁹⁻¹⁴ The box on page 59 illustrates one approach that shares many characteristics with others found in the literature.¹¹⁻¹⁵ The key feature is that students are mentally engaged in constructing (or, often, dismantling and reconstructing) their own knowledge. A student will accept a scientific conception over an erroneous belief only if:

- ▷ the student understands the meaning of the scientific conception
- ▷ the scientific conception is believable, that is, compatible with other conceptions held by the student
- ▷ the conception is useful to the student for interpreting or predicting other phenomena.¹⁶

Clearly we should not turn science instruction into a witch-hunt for students' misconceptions. To do so would sacrifice time that needs to be devoted to other important areas, such as laboratory work and instruction in problem solving. The constructivist view recognizes the time dependence of students' conceptual knowledge: Many misconceptions will disappear naturally as students gain expertise. However, to ignore how students are constructing the concepts they are taught in science leads to inefficient learning. We need to become aware of how students are thinking by making the communication process in instruction a two-way street. This would seem like an impossible task in large classes, since managing a highly interactive lesson becomes difficult with a large number of students; yet this approach has been used successfully by some high school physics teachers¹² and even in large college lecture environments.¹³

Problem solving

In addition to developing an accurate conceptual knowledge base, students need to be able to apply concepts to solve problems. The extensive research literature on problem solving provides us with considerable guidance on effective instructional strategies. By contrasting the

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A Constructivist Classroom Dialogue

The teacher has previously introduced the concept of acceleration. The teacher now presents some simple situations in order to explore the students' understanding of the concept in concrete contexts.

Teacher: Suppose I toss a ball straight up into the air like this (*demonstrates*). What is the ball's acceleration at the top of the trajectory?

Student 1: Zero.

Student 2: Yeah, zero.

T: Why is it zero?

S1: Well, at the top the ball stops moving, so the acceleration must be zero.

T: OK. If I place the ball on the table so that it doesn't move, is it accelerating?

S2: No. It's not moving.

T: What if I roll the ball across the table so that it moves at a constant velocity (*demonstrates*). Is the ball accelerating in that case?

S1 & S2: Yeah.

Student 3: No way! If the ball is rolling at a constant speed it doesn't have any acceleration because its speed doesn't change.

S2: No . . . listen. The ball had to have an acceleration to get to the speed it had.

S3: Yeah, but once it rolls at a constant speed it can't have any acceleration, 'cause if it did it would roll faster and faster.

S2: I'm not sure. You're confusing me.

T: What's the definition of acceleration?

S1: It's the change in speed over the change in time.

T: Close but not quite. It is the change in *velocity* over the change in time. Speed doesn't care about direction, but velocity does. At any rate, apply your definition to the ball rolling on the table.

S2: Well, I guess since its speed—I mean velocity—doesn't change as it rolls, it can't have an acceleration.

T: Do we agree on this case?

S1: Yeah.

S2: I guess so.

T: So it appears that an object can have a zero acceleration if it is standing still or if it is moving at a constant velocity. Let's reconsider the case where the ball is at the top of its trajectory (*demonstrates again*). What is the ball's acceleration when it is at the top?

S3: It would be zero because the ball is standing still at the top. It's not moving—it has to turn around.

S2: I think it might be accelerating because it gets going faster and faster.

S1: Yeah, but that doesn't happen until it gets going again. When it's standing still it's not accelerating.

The teacher could pursue various directions from here. One might be to pose a related situation. Another avenue might be to revisit the definition of acceleration and ask students to apply it during the time interval just prior to the ball's reaching the top and just after the ball starts its descent.

performance of skilled problem solvers with that of unskilled problem solvers, we have begun to form a picture of how to guide beginners through the intricate maze that leads to skilled performance.

The salient findings in studies of problem solvers are often discussed within two broad categories: knowledge organization and knowledge use. The physics knowledge of skilled problem solvers can be thought of as organized in a hierarchical, richly interconnected network, whereas the physics knowledge of beginners can be thought of as a somewhat amorphous network.¹⁷ (See figure 2.)

Skilled problem solvers use their knowledge to analyze problems qualitatively before resorting to mathematical manipulations.¹⁸ They look for the underlying principles and concepts that they could apply to solve the problem, and a general procedure for applying them. In contrast, unskilled solvers tend to see only the surface characteristics of problems and generally plunge into formulaic approaches without first analyzing problems qualitatively. (The box on page 60 illustrates how these behaviors would manifest themselves in solving particular problems.)

Traditional problem-solving instruction may inadvertently encourage students to use formulaic approaches. The teaching of problem solving in physics typically consists of cycling through three steps: The instructor first presents concepts, then illustrates their use in solving problems and finally assigns lots of problems for students to solve on their own. Although instructors often mention what principles and concepts are being applied when they work out problems in front of a class, they generally only write down the associated equations. Consequently, students take their lead from the mathematical aspects of the solution, not from the conceptual aspects. Students perceive that manipulation of equations generates answers to problems and that principles and concepts are abstractions that bear little relevance to this process.

The evidence is clear that students taught problem solving with this traditional approach can achieve good grades on exams but can still display little understanding of the concepts underlying the problems' solutions.^{3,7,8} Instruction that emphasizes the role of conceptual, qualitative analyses (for example, teaching students to perform qualitative analyses of problems, as shown by the skilled problem solver's answers in the box on page 60) appears to be more effective.^{13,19,20}

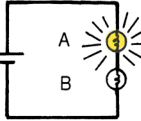
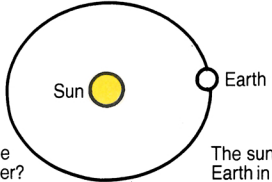
In general, our goal in problem-solving instruction should be to promote "higher-order thinking," which has been characterized in terms of nine attributes.¹ Higher-order thinking:

- ▷ is nonalgorithmic
- ▷ tends to be complex
- ▷ often yields multiple solutions
- ▷ involves nuanced judgments
- ▷ involves the application of multiple criteria
- ▷ often involves uncertainty
- ▷ involves self-regulation of the thinking process
- ▷ involves imposing meaning on or finding structure in apparent disorder
- ▷ involves considerable mental effort.

Strategic instruction

The preceding discussion suggests a role for science teachers that is drastically different from the traditional role of transmitter of knowledge. More specifically, instruction in science that is guided by our knowledge of how students learn, which I shall call "strategic instruction," requires that teachers be well versed in three important areas:

- ▷ *Content.* Teachers must have sufficient command of

Question	Misconception(s)
1. A ball is tossed vertically. What force or forces act on the ball when it is half way up to the top of its trajectory?	 The force of the hand.
2. A ball is shot through a hollow curved tube resting on a table. Draw the path of the ball when it emerges from the tube.	 (The more turns in the tube the more students who draw this path.)
3. Two different kinds of lightbulbs are connected in series to a battery. Explain why bulb A is lit and bulb B is not.	 The electricity gets used up in bulb A before it gets to bulb B. Bulb B is burnt out.
4. Why is it warmer in the summer than in the winter?	 The sun is closer to the Earth in the summer.

the content of science to distill the big ideas and methodology from the less useful facts and rote procedures. They need to be able to recognize when a student's conceptual knowledge is incomplete or inconsistent with scientific concepts.

▷ *Learning mechanisms and students' thinking.* Teachers need a working knowledge of the cognitive research literature as it pertains to learning. They need to know what constructivism implies for classroom instruction.

▷ *Instructional strategies.* Teachers need a working knowledge of approaches for encouraging and monitoring the conceptual understanding students possess. They also must integrate conceptual knowledge into instruction about problem solving.

Two important points should be kept in mind concerning teachers' mastery of these three areas. First, the weakness of teachers in each of these areas differs depending on grade level. The bleakest situation is in the elementary grades. It appears that few teachers at this level focus on children's ideas, predictions and explanations; science instruction in the elementary grades is based on the transmission model.^{9,10} In addition, most elementary school teachers have virtually no scientific knowledge, as the college science requirement for elementary education majors is minimal. This is unfortunate, given the wide variety of topics covered in typical science textbooks for the elementary grades. The view that science is a process of inquiry that allows us to organize phenomena under a few powerful principles is foreign to most teachers at this level.

At the high school level, the problem of lack of knowledge of the content of science is less severe, although there are a surprising number of physics teachers whose formal training was in one of the other sciences. The major concern with high school instruction is teachers' lack of knowledge about how their students think and about constructivist epistemology.²¹ Consequently, typical high school physics instruction emphasizes formulaic manipulations at the expense of qualitative reasoning. Further, the pressure to cover a long list of topics forces teachers to become transmitters of knowledge and leaves little time for reflection on the deep significance of the concepts. It would be better to teach fewer topics with enough depth to help students achieve a deep conceptual understanding, instead of many topics at a superficial

Common misconceptions in physics.

Traditional instruction based on the "transmission model" is often inadequate to overcome misconceptions. **Figure 1**

Overcoming Misconceptions

A constructivist approach to overcoming the first misconception shown in figure 1 could involve the following steps:

Probe for misconception. Toss a coin or ball vertically up and ask students to enumerate the forces acting on it when the object is halfway to the top of its trajectory.

Ask questions to clarify students' beliefs: Does the "force of the hand" change in magnitude or direction? What happens to this force at the top of the trajectory and on the way down? Is this force active in other situations, such as rolling a ball on top of a horizontal surface? When does the "force of the hand" act on the ball?

Suggest events that contradict students' beliefs: Suppose I push on you—how do you know when I stop pushing on you? How does the ball "know" that the "force of the hand" is still acting on it? If the ball experiences the force of the hand after it leaves the hand, why can't one control this force while the ball is in the air?

Encourage debate and discussion. Promote fruitful, nondisparaging debate among students as they take different sides in the ensuing argument. Encourage students to apply physics arguments, concepts and definitions.

Guide students toward constructing scientific conceptions. How one guides students depends on their answers to the teacher's questions and on the issues raised during the discussion and debate. One could involve the students in:

▷ a synthesis of their responses to questions and situations, with a discussion of how consistent those responses are with the scientific conception or other observations

▷ a discussion of "thought experiments" that in principle could measure the "force of the hand"

▷ a discussion of what the motion would be like with and without the "force of the hand" from the perspective of Newton's second law.

▷ the design and execution of experiments to test hypotheses.

Reevaluate students' understanding. Ask questions and pose situations that allow students to display whether or not they have acquired the appropriate understanding: When is the "force of the hand" acting on a ball that is thrown up? What are the forces acting on a cannonball that was shot out of a cannon while it is airborne? What is the difference, if any, between the cannonball and the thrown ball?

The second point regarding the three areas mentioned above is that they are inextricably related and should be dealt with as a package. Educating teachers in any one area will not markedly improve instruction. For example, one group of elementary school in-service teachers who were trained to elicit students' preconceptions and to encourage discussion and debate were nonetheless poor at recognizing misconceptions that arose during the discussion, due to their lack of content knowledge.¹⁰ Even when they recognized a misconception they were unable to present examples of phenomena that were at variance with the misconception, or to offer any guidance to help students grapple with the inconsistency between their beliefs and scientific concepts. Conversely, knowing how to identify common misconceptions is not enough to enable the teacher to assist students in overcoming them if the teacher lacks a working knowledge of effective instructional strategies.

Commercially available science curricula

We now consider the science and physics textbooks commercially available to pre-college teachers in the light of some pivotal questions:

- ▷ Do textbooks reflect constructivist epistemology?
- ▷ Do they portray science as a process of inquiry?
- ▷ Do they encourage qualitative reasoning?
- ▷ Do they challenge students to reflect on important ideas?
- ▷ Do they help students construct hierarchical knowledge networks and apply this knowledge to solving problems?

The first thing that is readily apparent upon inspecting textbooks at all levels is that they are mostly clones of one another. The physical science portions of a typical science series for grades 1–5 consist largely of the same topics, which are revisited each year: mass, length, volume, gravity, forces, work, energy, sound, light, electricity, magnetism, atoms and so on. The aim is not to in-

Skilled And Unskilled Problem Solving

By asking students questions about specific science problems, one can elicit the very different approaches they take toward problem solving in general. Typical responses by skilled and unskilled problem solvers to questions about the following set of problems are given below.

1. A 1-kg stick of length 1 m is placed on a frictionless horizontal surface and is free to rotate about a vertical axle through one end. A 50-g lump of clay is attached 80 cm from the pivot. Find the net force between the stick and the clay when the angular velocity of the system is 3 rad/sec.

A. A stick of length 1.5 m and mass 0.2 kg is on a frictionless horizontal surface and is rotating about a pivot at one end with an angular velocity of 5 rad/sec. A 35-g lump of clay drops vertically onto the stick at its midpoint. If the clay remains attached to the stick, find the final angular velocity of the stick-clay system.

B. A 60-kg block is held in place on a frictionless inclined plane of angle 25°. The block is attached to a hanging mass by a light string over a frictionless pulley. Find the value of the hanging mass so that the block does not move when released.

Question: Which of problems A and B would be solved most like problem 1? Explain your answer.

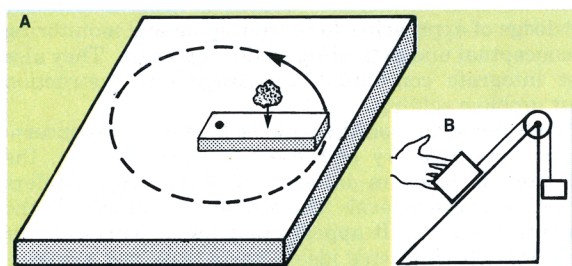
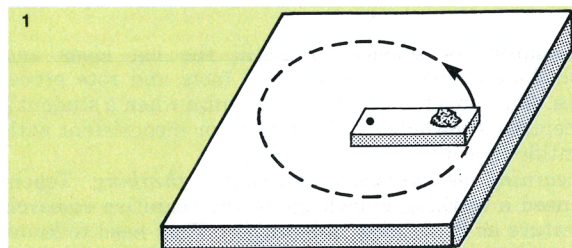
Typical skilled problem solver's answer: Problem B. Both 1 and B involve the application of Newton's second law.

Typical unskilled problem solver's answer: Problem A. Both 1 and A involve a rotating stick with a lump of clay attached.

Note that skilled problem solvers take their lead from the problems' underlying principles, whereas unskilled problem solvers see only the problems' surface characteristics.

Question: Describe how you would go about solving problem 1.

Typical skilled problem solver's answer: The clay accelerates as it moves in a circle; the net force needed to keep

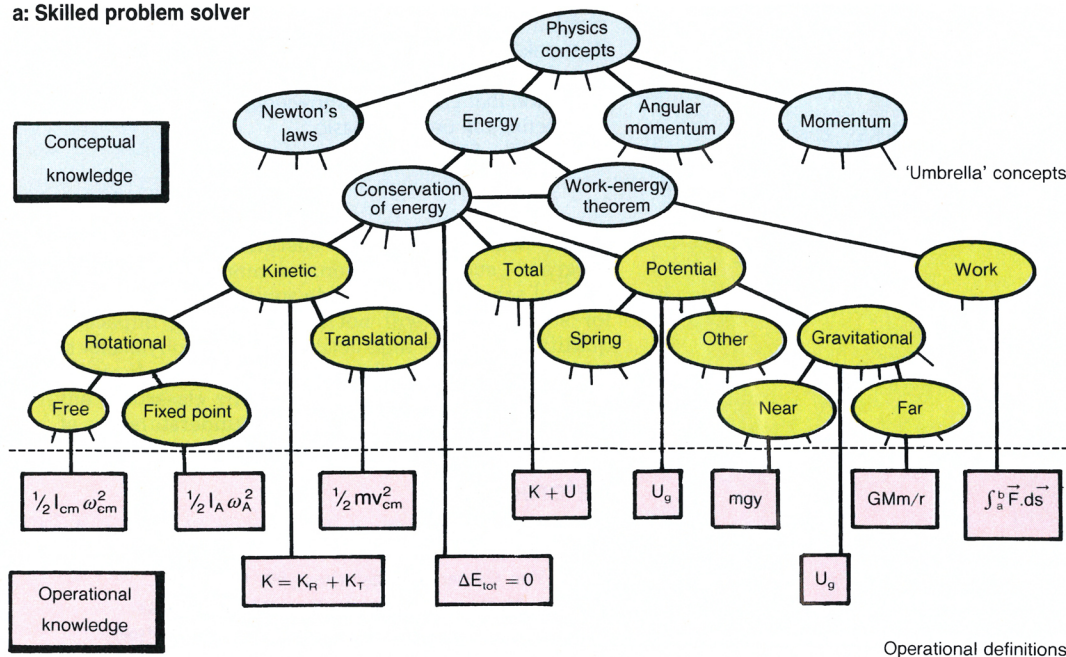


the clay going in a circle is provided by the horizontal force between the stick and the clay. Therefore, apply Newton's second law and set the net force on the clay equal to its mass times its centripetal acceleration. Then solve for the magnitude of the force.

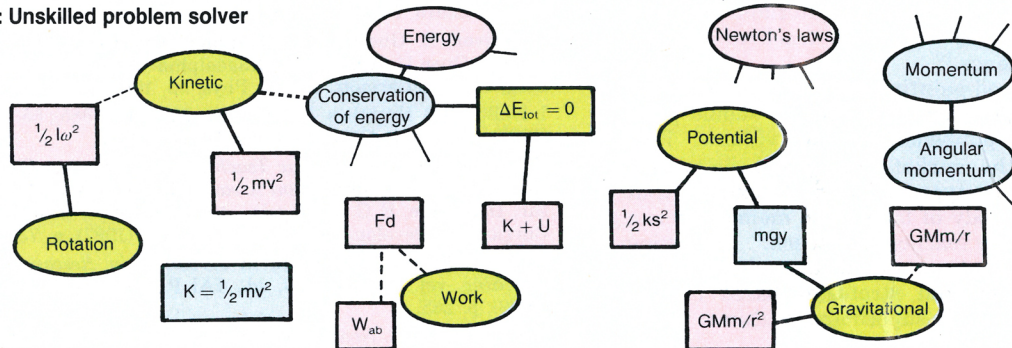
Typical (competent) unskilled problem solver's answer: The stick and the clay are both moving in a circular path, so I would probably have to use ω and $\frac{1}{2}\omega^2$ for the stick, and mvR and $\frac{1}{2}mv^2$ for the clay. I am told values for the mass of the clay and stick, so I have m , and I can find l by looking up the expression for a stick pivoted at one end in a table and plugging in to get a number for it. The force for something moving in a circle is mv^2/R , so I think I have enough to get an answer.

Note that skilled problem solvers perform a qualitative analysis during which they identify the applicable principle and devise a procedure for solving the problem. In contrast, novices jump to formulaic approaches, often writing down expressions that are irrelevant for solving the problem. The principle and the procedure are usually lacking from novices' approach.

a: Skilled problem solver



b: Unskilled problem solver



Representations
of how
elementary
classical
mechanics
knowledge might
be organized in
the minds of a
skilled (a) and an
unskilled (b)
problem solver.
Figure 2

crease students' understanding of the concepts involved but to provide more detailed facts at successive grade levels. New scientific words are presented in boldface type to emphasize their "importance." The "main ideas" listed in the back of each chapter are mostly definitions and facts—not ideas.

Although rare, some texts contain useful explanations of concepts, but these are not highlighted, nor are students challenged to think about the underlying meaning of the concepts. The coverage of a concept such as "work" typically consists of a simplistic definition and a couple of examples of situations in which work is being done (for example, pushing a box along the floor). After I recently read the unit on "work" in a typical elementary-level textbook, I could not help but ask: So what? Why is this useful? Why do I have to know this definition or fact? How is this science?

Presented with these types of textbooks, an adult not trained in science would conclude that science is a list of facts and definitions to be committed to memory, which is precisely how science is taught at this level.⁸ To teach in the constructivist style from such a textbook, a teacher would need to reorganize its presentation, emphasizing the usefulness and application of concepts through an inquiry approach. However, as has already been argued, elementary school teachers lack the perspective to accomplish this reorganization.

At the middle school level, the size of the type gets smaller, but the textbooks remain similar in style and content to those used in the elementary grades. At the very beginning of a popular text we are told that "Science is the knowledge of all the facts that are known about the world and the methods or processes used to learn or explain these facts." True to this definition, the remainder of the book presents the facts of science. Furthermore, laboratory activities in most middle school curriculums do not promote a spirit of inquiry but rather are designed to verify known phenomena, which promotes an authoritarian view of science as a body of factual knowledge that is revealed only if the scientific method is followed.²²

In high school, teaching students to solve "textbook problems" plays a major role in physics instruction. Textbooks at this level portray problem solving as algebraic manipulation and encourage a formulaic approach with minimal use of conceptual knowledge. Figure 3 shows a typical worked-out problem based on an example found in one of the most popular high school physics textbooks. Almost nothing in the worked-out examples that appear in the popular textbooks allows a student to gain a perspective on how to integrate conceptual knowledge into problem solving. What impression is a student to form about problem solving after reading countless examples like this?

The answer to all five questions posed at the

Conservation of Energy

A large chunk of ice with a mass of 12.0 kg falls from a roof 7.50 meters above the ground. a. What is the kinetic energy of the ice as it reaches the ground? b. What is its speed as it reaches the ground?

Given: $m = 12.0 \text{ kg}$ **Unknown:** a. KE_i b. v_f
 $g = 9.80 \text{ m/s}^2$ **Basic equation:** $PE_i + KE_i = PE_f + KE_f$
 $h = 7.50 \text{ m}$
 $KE_i = 0$
 $PE_f = 0$

Solution:

a. $PE_i + KE_i = PE_f + KE_f$
 $mgh + \frac{1}{2}mv^2 = PE_f + KE_f$
 $(12.0 \text{ kg})(9.80 \text{ m/s}^2)(7.50 \text{ m}) + 0 = 0 + KE_f$
 $880 \text{ J} = KE_f$

b. $KE_f = \frac{1}{2}mv_f^2$
 $v_f^2 = \frac{2KE_f}{m} = \frac{(2)(880 \text{ J})}{12.0 \text{ kg}}$
 $v_f = \sqrt{147 \text{ m}^2/\text{s}^2}$
 $v_f = 12.1 \text{ m/s}$

beginning of this section is clearly no. And the shortcomings of commercial instructional materials are only amplified by the degree to which teachers rely on textbooks to teach science.¹⁰

Having just finished painting such a bleak picture of commercially available science textbooks, I should point out that commercial publishers are not villains. Publishers simply fulfill the market's wants, and the market appears to demand these types of books. A textbook that portrays science as a body of facts to be memorized is a textbook from which any teacher can "teach." Possessing sufficient knowledge about content, about students' thinking and about instructional strategies based on the constructivist perspective is superfluous within a teach-the-facts science curriculum.

There are some excellent science curricular materials. (Gerhard Salinger reviews some in his article on page 39.) But these are often labeled "experimental," and many are not commercially available. Some are still under development.

Where do we go from here?

It is apparent that science education in grades K-12 needs reform. The problems that need to be addressed are complex, and simplistic or shortsighted solutions are not likely to succeed. Both pre-service and in-service teachers need to have their knowledge upgraded in three areas: science content, how students think and learn, and instructional strategies. All three areas should be addressed as a coherent package.

The reform movement needs the participation of scientists as much as it needs the participation of teachers, cognitive scientists and textbook publishers. Its success will require a collaborative effort in which all parties pool their knowledge and talents: Scientists provide accurate, up-to-date scientific content and insights on problem solving, teachers provide expertise about children and classroom dynamics, and cognitive scientists provide expertise on learning and instruction. Textbook publishers need to reflect our current understanding about learning and instruction in their products.

I hope that physicists become actively involved in the reform movement both nationally and locally. I offer two caveats for those wishing to do so. First, the involvement

Worked-out example based on an actual problem from a popular high school physics textbook. The solution presented consists entirely of algebraic manipulation, with no indication that conceptual knowledge is useful in selecting the correct "basic equation." **Figure 3**

of physicists must be a sustained effort. Short-term programs, such as occasional demonstrations or lectures at local schools, may provide some interest and diversion for students but will not have a lasting impact on the quality of science instruction. Second, physicists should be conversant with the relevant research literature on learning and with the reality of the classroom environment. Only in this way can our understanding of how students learn be put to good use.

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