

TEACHING PHYSICS: FIGURING OUT WHAT WORKS

Research on three questions is improving instruction: What is involved in understanding physics? What do students bring to physics classes? How do they respond to what they are taught?

Edward F. Redish and Richard N. Steinberg

Physics faculty members often come away from teaching college-level introductory courses deeply dismayed about how little their students have learned. The growing importance of having a workforce that is literate in science and technology makes this situation more than an academic problem.

One source of difficulty is that even though more than 95% of students in introductory physics never take another physics class,¹ introductory courses are often variations on courses designed for the prospective professional physicist. They treat many topics superficially to provide a context for the later study of physics, and they emphasize mathematical manipulations and structures that lay the groundwork for more advanced study.

Fortunately, research findings suggest that, with the right kind of learning environment, a single pass through a physics course can be a valuable learning experience for the majority of college students.² To figure out what we can offer students in introductory physics (and beyond), we need to find answers to three distinct but interlocking questions:

▷ What is involved in understanding and using physics? Answering this question requires careful observation and analysis of the content of physics courses and of the behavior of expert physicists.

▷ What do students bring to physics classes? How students hear and interpret the material presented to them depends heavily on the experiences they bring to the class. Everyone has some sense that force is necessary to maintain velocity when walking, driving or pushing something along the floor. Thus, Newton's second law (brought to the student's attention in experiments like the one shown in figure 1) is inconsistent with the way in which many of our students make sense of their experiences in the world.

▷ How do students respond to physics instruction? We often assume that students will respond as we did—or rather, as we might have wished we did, knowing what we know now. To design effective instruction, we must learn how students really respond.

Over the past two decades, an increasing number of physicists have been turning their research attention to problems of physics education. A dozen physics education research programs now exist in research physics departments around the country. One benefit of this development is that it has brought a physicist's perspective and expertise to bear on the study of how to make our physics

classes work effectively. A physics department benefits from the development of more effective teaching methods tuned to its particular situation, and from building links to other physics education researchers. Physics education research is a growing subfield of physics.

Discipline-based education research

When it gets difficult to make sense of a situation, we need to become researchers—to combine observation and analysis to figure it out. When the subject is our students, we need to become physics education researchers. At the heart of physics education research is the need for physics instruction to undergo a shift in emphasis from "What are we teaching and how can we deliver it?" to "What are the students learning and how do we make sense of what they do?" To make this shift, we need to listen to the students and find ways to learn what they are thinking. Only then can we begin to make sense of how students learn physics in a way that helps us improve our courses.

What is required of physics education researchers goes well beyond how even good teachers interact with their students. The two of us, for example, have observed classes and seen frequent instances of an instructor listening, but failing to recognize the student's real difficulty. For instance, in a junior level electronics class, a student asked a question about a comparison of currents at two points on a single branch of a relatively complicated circuit. Like many physics instructors, the one in this class was a concerned and dedicated teacher. He listened carefully and recognized that the student was confused. He proceeded to give a detailed description of how the entire complicated circuit worked. However, because the current was necessarily the same throughout the branch of the circuit, it was likely that the student's difficulty was a deep one—and not addressed in the instructor's response; namely, that somehow the current was "used up" en route.³ The student politely nodded, no better off than before, and the teacher moved on.

In trying to find out what students' real difficulties are, physics education researchers use a variety of tools. One task is to determine the "state space"—the range of most common possibilities. One way to do this is to carefully interview a number of students, letting them describe what they think about a particular situation or having them work through a problem. The researcher encourages the students to "think aloud" and to explain their reasoning. The goal isn't to help the students come up with the "correct" answer, but rather to understand their thinking. Interviews are videotaped, transcribed and analyzed by several researchers. Figure 2 shows a typical interview session. Interviews often reveal new insights into the ways in which students think about physics that are surprising even to the most skilled and

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FIGURE 1. INTERACTIVE computer-based tutorial on force and motion. Students work with a teaching assistant (standing at right) and a computer in this classroom lesson. A motion sensor provides real-time graphs of the position and velocity of a cart propelled by a fan.

experienced instructors.

The information from interviews can be used to develop examination questions. Such questions must place a strong emphasis on having students explain their thinking. Otherwise, students often replay poorly understood memorized patterns. Then, the evaluator may fill in the needed understanding from his or her own superior knowledge and fail to recognize where the students' difficulties really lie.

After a good understanding of student confusions and difficulties is obtained, multiple-choice tests or surveys can be carefully designed with the "distractors" selected from common wrong answers given by students. These tests and surveys can then be given to large numbers of students, and distribution functions can be obtained. One needs to interpret the results carefully, because multiple-choice tests or surveys give very limited views of complex situations.⁴

Components of problem solving

Problem solving is consistently rated as the most important skill learned in undergraduate physics. To understand what is meant by problem solving, we have to look carefully at what it is that expert problem solvers actually do. In the 1980s, physicists, educators and cognitive scientists carried out extensive studies of how different people approach physics problems.⁵ (See Frederick Reif's article on scientific approaches to science education, *PHYSICS TODAY*, November 1986, page 48.) As part of a study at the University of California, Berkeley and later at Carnegie-Mellon University, Jill Larkin and Frederick Reif compared the problem solving approaches of an expert

with that of an excellent introductory physics student.⁶ By "excellent," they meant a student who was doing very well on both homework and examinations. Larkin and Reif characterized the expert's problem solving as making use of, among other things, a strong understanding of physics concepts (what the physics is about), and a well-developed knowledge structure (how the physics fits together). In contrast, they characterized the student's problem solving as being dominated by superficial mathematical manipulations without deeper analysis.

Concepts. Because a good understanding of concepts appears to be a prerequisite for expert problem solving, much effort has gone into identifying fundamental concepts and the difficulties that students have with them. For the past 20 years, Lillian C. McDermott and the Physics Education Group at the University of Washington have been leaders in carrying out this research.⁷ (See McDermott's article about research on conceptual understanding in mechanics, *PHYSICS TODAY*, July 1984, page 24.)

McDermott and other physics education researchers have documented that even after studying physics, students have an understanding of fundamental concepts that is usually weak. For example, the study detailed in the box on page 27 shows some of the difficulties students have in making sense of the concept of a photon. (See references 8 and 9 for further details.) Note that the interviewed students may well be able to answer standard problems on the photoelectric or the Compton effect. However, the way they think about the photon inhibits the way they make sense of the nature of light.



FIGURE 2. INDIVIDUAL DEMONSTRATION INTERVIEW. In this particular interview, an upper-level physics major (right) is asked how conductors, insulators and semiconductors would behave in a circuit. When left to explain what they think about relatively simple tasks, students often reveal surprising beliefs about the physics that they have studied.

Evaluating student understanding of basic concepts requires the use of the full range of physics education research observation tools: interviews, open-ended exam questions and carefully constructed multiple-choice tests. To study distribution functions and student responses on a large scale, multiple-choice tests are the easiest tool to employ.

David Hestenes and his colleagues at Arizona State University have developed the most extensively used multiple-choice diagnostic to date.¹⁰ The Force Concept Inventory (FCI) is a 29-question test that has helped increase awareness of the extent of student conceptual difficulties in mechanics. The test covers basic concepts from introductory mechanics, but the wording is couched in common speech rather than in that of a typical physics problem. The distractors are based on the most commonly held incorrect beliefs as determined by interviews and open-ended problems. Figure 3 and the box on page 29

show sample questions from the FCI. At the University of Maryland, we administered the FCI to 16 different lecture classes over five years. In our study, 767 students completed the FCI both before and after instruction. Of these students, 238 had traditional instruction and 529 had modified instruction (described below). Prior to any instruction, only 50% of the students gave the correct answer to the item shown in figure 3 (choice E). Most of the students answering incorrectly appeared to focus on the instant when the blocks are at the same position, not when they are moving at equal velocities. Unfortunately, after traditional instruction the success rate was 47%. Similar results are evident in other examples (see the box on page 29).

The difficulties experienced by the students in our study were not limited to their performance on multiple-choice questions. In fact, looking merely at student performance on multiple-choice diagnostics can be very misleading.⁴ However, results comparable to those described in the previous paragraph have been observed using other tools, including open-ended questions, problems and interviews.¹¹

Expectations. Studies of expert problem solvers indicate that there is much more to being a good problem solver than having agility with mathematical manipulations and a good knowledge of concepts. For many students in introductory physics, what is lacking is the understanding that concepts are relevant to problems and that physics is more than a set of facts and equations to be memorized. This shortcoming does not necessarily go away, even given our "ideal" situation—physics majors trained for graduate school. At Maryland, we have heard numerous complaints from advisers of physics PhD students who approach their research by "turning the crank" without thinking about the physics.

In a study at Berkeley, David Hammer carefully investigated the views about physics of a small number of students in a calculus-based physics course.¹² He interviewed students throughout the course and observed how they approached complex problems. He found that most of the students had attitudes about the nature of physics and how one approaches problems that were counterproductive to helping them develop a strong understanding of physics or expert problem solving skills. He classified their beliefs along three dimensions: independence/authority, coherence/pieces

Dimensions of student "expectations"

	Favorable	Unfavorable
Independence	Learns independently, believes in own need to evaluate and understand	Takes what is given by authorities (teacher, text) without evaluation
Coherence	Believes physics needs to be considered as a connected, consistent framework	Believes physics can be treated as separate facts or "pieces"
Concepts	Stresses understanding of the underlying ideas and concepts	Focuses on memorizing and using formulas
Reality link	Believes ideas learned in physics are useful in a wide variety of real-world contexts	Believes ideas learned in physics are unrelated to experiences outside the classroom
Math link	Considers mathematics to be a convenient way of representing physical phenomena	Views the physics and the math as independent with no strong relationship between them
Effort	Makes effort to use available information to modify and correct thinking	Does not use available information to modify thinking

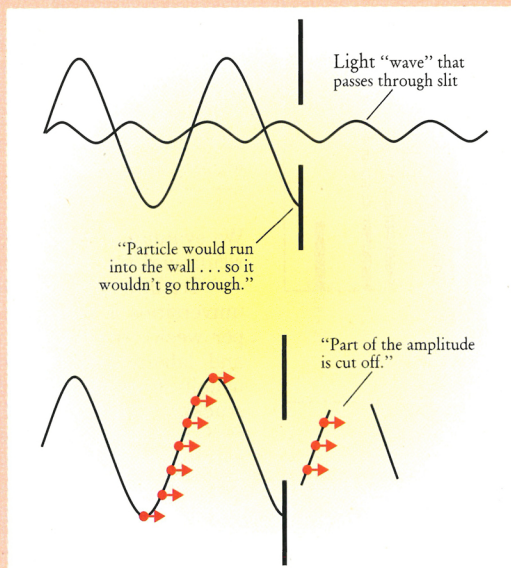
Student attitudes can be at either extreme or somewhere in between. The percentage of students with favorable attitudes tends to deteriorate as a result of traditional instruction.

Box 1. Students Misinterpret Representations

What was Dirk *really* thinking about light after he successfully completed introductory calculus-based physics? To find out, I showed him a small light bulb, a piece of cardboard with a rectangle cut out and a sheet of paper.⁸ "What would you see on the paper if the room light were turned off and the little bulb on?" I never did the experiment, I just asked what if. Dirk drew a picture of perpendicular sine curves and called one the "electric flux" and the other the "magnetic part"—a strange approach given that the problem can be easily solved with a ray diagram. "So what would you see on the screen?" Dirk eventually drew straight lines and came up with the correct answer.

"What if the slit were narrower?" Dirk said that geometrical optics applies as long as the slit is wider than the wavelength of light, because "the waves are still making it through the slit." Not only is this answer incorrect, but it is an unusual way to describe light. "What if the width of the slit were a little bit less than the wavelength of the light?" Dirk stated that now a diffraction pattern will occur; the magnetic part of the wave will not "be affected" but the electric part "will be affected . . . [the slit] knocks it out of whack." Dirk explained how the amplitude of the electric wave hits the sides of the slit causing the diffraction, but the magnetic part of the wave gets through because it is lined up with the long dimension of the slit.

We interviewed 48 students who had finished introductory



calculus-based physics. Most were among the best in the class. The goal of each interview was to probe what the student was thinking without affecting that thinking. We asked students to make predictions and explain their reasoning. In accounting for their predictions, about half of the students had some sort of spatial interpretation of the amplitude of light. The figure shows two examples. Most of the students did not do as well as these two.

This type of research has guided the development of tutorials.⁹ For physical optics, students supplement the standard mathematically oriented textbook and lecture by observing water waves propagating freely and through slits of various widths, applying principles of superposition when there is more than one wave present, and building an analogy with the behavior of light. Students build an understanding of the various models they are using, and consider both the values and limitations of the models. There is an emphasis on the reasoning that is required to develop and apply important concepts and principles.

In some lecture classes at the University of Maryland, tutorials have replaced the traditional quantitative recitation sections. Not surprisingly, we have found that tutorial students do better on conceptual and qualitative questions. However, we also have found that tutorial students do considerably better on a standard textbook-like problem—60% versus 16% correct. —R. N. STEINBERG

and concepts/equations.

At Maryland, to probe the distribution of these attitudes in large calculus-based physics classes, we developed the Maryland Physics Expectations survey, a set of 34 statements that students are asked to agree or disagree with.¹³ These probe the Hammer dimensions and three more: a physics–reality link, a math–physics link and an effort variable. (See the table on page 26.) We describe these views as "cognitive attitudes," or expectations.

We presented our survey to a group of expert physics instructors and asked them to choose the answers they would like their students to give. The experts agreed on the polarity (whether the students should agree or disagree) of the responses nearly 90% of the time. We refer to a student opinion that agrees with the expert polarity as favorable, and one that disagrees as unfavorable.

In our study of student expectations, we found that, after three semesters of traditional instruction in calculus-based physics, half of our engineering physics students agreed with the following statement from the Maryland Physics Expectations survey: "All I learn from a derivation or proof of a formula is that the formula obtained is valid and that it is OK to use it in problems."

Our instructors carefully presented critical derivations in lecture. They used them to show

the applicability of the resulting formula and its relation to fundamental principles. Nonetheless, many of our students chose to ignore the teacher's explicit emphasis. Their view of what they expected to get out of the class was the use of formulas, not an understanding of the limitations of those formulas or the relation of the formulas to fundamental principles and concepts.

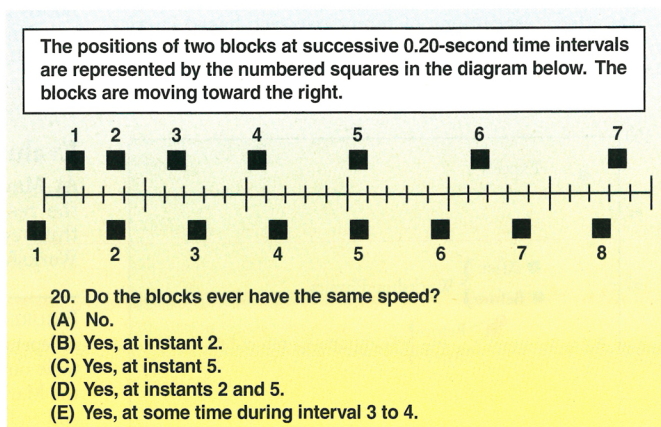


FIGURE 3. FORCE CONCEPT INVENTORY question. Half the engineering students at the University of Maryland answer this incorrectly both before and after traditional instruction. However, a research-based active learning environment can improve their conceptual learning.

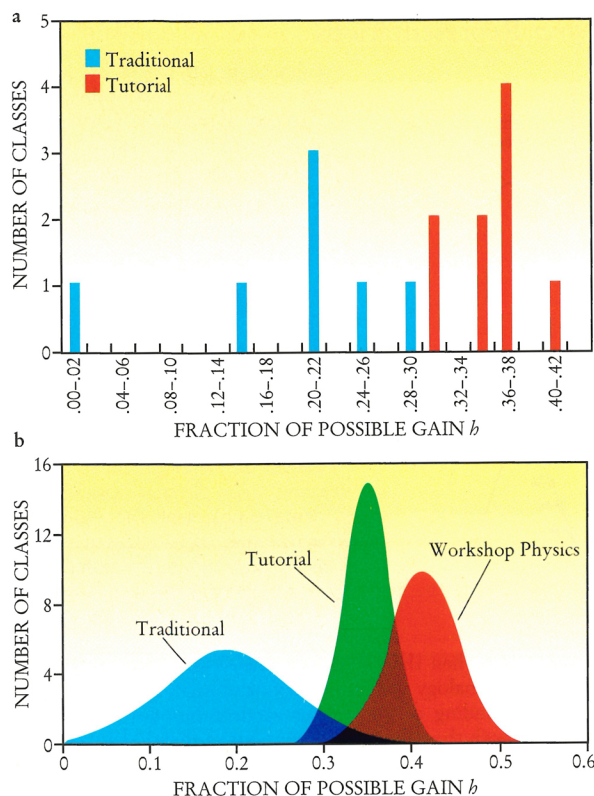


FIGURE 4. GAINS IN CONCEPTUAL UNDERSTANDING of mechanics. **a:** Histogram of gains, as measured by the Force Concept Inventory, due to traditional and tutorial classes at the University of Maryland, College Park. **b:** Gaussian fit to histogram of FCI gains in traditional, tutorial and Workshop Physics classes at eight institutions. Student performance is better after going through learning environments based on physics education research than after going through traditional learning environments.

We evaluate two specific examples of research-based curricula and traditional instruction below.

Traditionally, introductory physics at large research universities is taught in large lecture classes (2–4 hours per week), small group recitations (1–2 hours per week) and laboratories (2–3 hours per week). Lectures are usually presented by a faculty member with little or no student participation. Lectures may include demonstrations and the modeling of the solution of sample problems. Recitations are often presented by teaching assistants. The TAs may answer student questions, but mostly they model solutions to the problem on the board. Students rarely participate actively.

At the University of Washington, McDermott and her collaborators have developed a replacement—called tutorials—for the recitations in traditional introductory classes.^{9,16} Instead of watching TAs model problem solving, students in tutorial work in groups of three or four on research-based worksheets. These carefully designed worksheets lead students to make predictions and compare various lines of reasoning to build an understanding of basic concepts. In addition to a lecturer, this model requires approximately one facilitator contact hour per week for every 15 students.

At Dickinson College in Carlisle, Pennsylvania, Priscilla Laws and her collaborators have developed Workshop Physics—a set of instructional materials for a nontraditional learning environment in which lectures, recitations and laboratories are combined in two three-hour lab-based sessions.¹⁷ (See Laws's article on calculus-based physics without lectures, *PHYSICS TODAY*, December 1991, page 24.) Students work in groups of two to four with sophisticated computer equipment that permits them to obtain high-quality data quickly and efficiently. This model requires an instructor and an assistant (such as a student who has completed the class) for about 30 students for six contact hours per week.

Note that in tutorials, only one hour per week differs from the traditional format, as the lecture, lab and text remain unchanged. Workshop Physics, however, modifies the entire course structure.

Evaluating research-based curricula

At Maryland, we recently completed a project studying the results of one semester of calculus-based physics in three educational environments: traditional, tutorials and Workshop Physics.¹¹ We evaluated students' conceptual

Building research-based curricula

In response to the elucidation of specific student difficulties in learning introductory physics, a number of physicists have produced curricula that focus specifically on teaching more effectively. In building these research-based curricula, developers combine two elements. They use their understanding, learned from physics education research, about what difficulties students really face. They combine this with educational structures and environments influenced by scholars of education and cognitive psychology who find that most students learn more effectively in active-engagement environments in which social interaction takes place.¹⁴ Finally, these elements are refined through successive delivery, research and redesign.

Detailed descriptions of many research-based curricula may be found in the proceedings of a 1996 international conference on undergraduate physics education.¹⁵

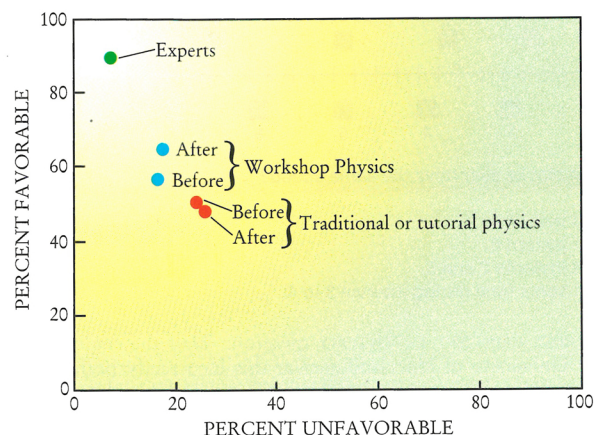


FIGURE 5. MIXED RESULTS. Plotted are the averages of the independence/coherence/concepts variables described in the table on page 26. The data were collected by administering the Maryland Physics Expectations survey at the beginning and end of the first semester of introductory calculus-based physics. The Workshop Physics data are from Dickinson College. The traditional/tutorial data are from three large research universities. Students' attitudes along these dimensions appear to deteriorate after traditional instruction but improve slightly after Workshop Physics.

Box 2. Students Hold Contradictory Views Simultaneously

On the final exam in one of my physics classes for engineering students, I gave this question on Newton's third law from the Force Concept Inventory.¹¹ One of my better students came to my office after the exam and was very upset. She expressed her confusion about which of the colliding vehicles felt the greater force, the small car or the large truck, and reported that she had changed her answer numerous times during the exam. "I know," she said, "that Newton's third law says they should be equal, but that can't be right, can it?" The classroom context led her to bring up her "physics class" model, Newton's third law, but the common-speech wording of the question led her to bring up her commonsense response—larger objects exert a larger force. Successfully learning Newton's third law was not enough for her to be comfortable with the situations in which it should be used.

When we gave this problem to large numbers of Maryland students as a pretest, only 30% chose the correct answer, E, while 66% chose A. After recitations, the number of correct

Imagine a head-on collision between a large truck and a small compact car. During the collision:

- (A) The truck exerts a greater amount of force on the car than the car exerts on the truck.
- (B) The car exerts a greater amount of force on the truck than the truck exerts on the car.
- (C) Neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
- (D) The truck exerts a force on the car but the car does not exert a force on the truck.
- (E) The truck exerts the same amount of force on the car as the car exerts on the truck.

answers rose, but only to 50%, with half of the students still giving answer A. After tutorials, the number of correct answers rose to 80% with only 20% choosing A. The question was given to 238 students in recitation and 529 in tutorials.

—E. F. REDISH

learning, the evolution of their cognitive attitudes about physics and their traditional problem solving abilities. We used a variety of tools, including detailed student interviews, open-ended examination problems and multiple-choice diagnostics.

Although each evaluation method provides different insights, the results of the different probes have been consistent. For brevity, we focus here on the results obtained with the FCI and the Maryland Physics Expectations survey.

It should be noted that although their coverage of topics is comparable to that of a traditional course, tutorials, Workshop Physics and many other innovative learning environments emphasize conceptual learning. However, the concepts covered in the FCI (such as acceleration and force) are widely recognized as universally important to learning introductory mechanics. One might be concerned that the extra effort spent on concepts in the research-based courses might be at the expense of other learning goals, such as problem solving. However, student problem solving skills and expectations in research-based learning environments are as good or better than those in the traditional classes.^{3,8,11}

Richard Hake at Indiana University studied student performance on the FCI. He collected FCI reports before and after instruction from more than 6500 students in 62 introductory physics classes.¹⁸ Hake found that interactive engagement classes using curricula based on physics education research consistently had higher gains on multiple-choice diagnostics. He also found that although classes at different institutions had widely different pre-FCI scores (ranging from 25% to 75%), courses with a similar structure achieved a similar proportion of the possible gain. That is, the Hake factor

$$h = \frac{\text{gain}}{\text{possible gain}} = \frac{\text{post-average \%} - \text{pre-average \%}}{100\% - \text{pre-average \%}}$$

serves as an appropriate figure of merit.

In our study at Maryland, we collected preinstruction and postinstruction FCI scores in a calculus-based physics course both for a traditional class with recitations and for the identical class with tutorials. During a five-year span, about half of the lecture classes were done in each mode, with students not being aware beforehand which model was to be used. We collected matched data from a total of 767 students with ten different lecturers. Seven classes were done with recitations and nine with tutorials.

The FCI was administered as an ungraded quiz during the first and last week of the course. Figure 4a displays the fractional gain. Two of the lecturers taught in both modes. They found that their classes' Hake factor improved by more than 0.15 when they used tutorials. We extended our study to more than 2000 matched students at seven additional institutions, including a number that were introducing the Workshop Physics curriculum. Our results show a Hake factor of 0.16 ± 0.03 for the traditional curriculum, 0.35 ± 0.03 for tutorials and 0.41 ± 0.02 for Workshop Physics. Figure 4b displays these results by replacing the histograms with Gaussian curves adjusted to fit the mean and standard deviation of the distribution and normalized to unity. Although it is encouraging to note that higher gains are possible, they are still much less than 1.

We used the Maryland Physics Expectations survey to probe the distribution and changes in student cognitive attitudes. Based on results from more than 1500 students from six colleges and universities, it is clear that many students come into physics with unfavorable views about the nature of learning physics. More worrisome is that these views tend to deteriorate after a traditional semester of university physics. After one semester of instruction in mechanics, almost no traditional or tutorial classes showed improvement in any of the variables. Indeed, the overall average of 1350 students at three large research universities deteriorated by about 1 standard deviation after one semester of instruction.

However, it does appear that, in certain modified learning environments, student views do evolve to be more favorable. In the Workshop Physics classes we studied, students showed a 2.5 standard deviation improvement on the average of the independence/coherence/concepts clusters. This is displayed in figure 5. In this plot, the percentage of students agreeing with the favorable response is plotted on the vertical axis, and the percentage giving unfavorable responses is plotted on the horizontal axis.

Improving instruction

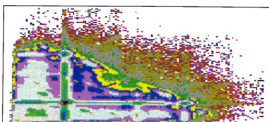
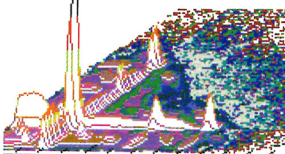
Our focus in this article on two of the elements that students need to master to become expert solvers of complex problems—concepts and appropriate cognitive attitudes—should not be taken to imply that they are the whole story. Additional research is still needed on many topics, including students' ability to apply concepts in problems, their reasoning and use of mathematics and the

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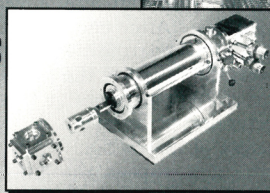
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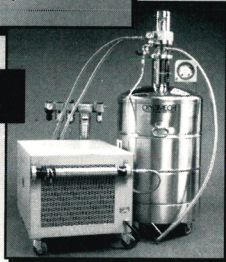
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impact of technological environments on what students learn. But the by-now large body of physics education research (reference 2 cites more than 200 items) has provided many solid and surprising insights that can help physics instructors improve their judgments about what is happening in their own classrooms. This research has led to a variety of curricular tools and techniques that can help instructors deliver more effective instruction.¹⁵ But what is perhaps most important is that the dialog within the physics community on what is effective in instruction is now well begun. We have started the process of developing, evaluating and cumulating a solid set of community knowledge on what works—and what it means for instruction to work.

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