

Transforming Physics Education

By using the tools of physics in their teaching, instructors can move students from mindless memorization to understanding and appreciation.

Carl Wieman and Katherine Perkins

The science community needs to change science education to make it effective and relevant for a much larger fraction of the student population than in the past. This need is the result of significant changes in the environment and society over the past several decades. First, society now faces critical global-scale issues that are fundamentally technical in nature—for example, climate change, genetic modification, and energy supply. Only a far more scientifically and technically literate citizenry can make wise decisions on such issues. Second, modern economies are so heavily based on technology that having a better understanding of science and technology and better technical problem-solving skills will enhance a person's career aspirations almost independent of occupation. Furthermore, a modern economy can thrive only if it has a workforce with high-level technical understanding and skills.

As a community, we must now ask ourselves, “How successfully are we educating all students in science?” This objective is very different from in the past, when the goal of science education was primarily to train only the tiny fraction of the population that would become future scientists. The new, broader educational need does not eliminate the need to educate future generations of scientists. However, improving science education for all students is likely to produce more and better-educated scientists and engineers. This claim is supported by data showing that the fraction of students who complete a physical science major in college is determined more by the students' ability to tolerate traditional physical science instruction than by their ability to do science.¹

For a variety of reasons, the physics community should and can take the lead in providing an effective and relevant science education for all students. Moreover, this is in their enlightened self-interest. A better-educated citizenry would better appreciate the value of supporting physics research.

But what specifically do we mean by *effective* physics instruction? It is instruction that changes the way students think about physics and physics problem solving and causes them to think more like experts—practicing physicists.² Experts see the content of physics as a coherent structure of general concepts that describe nature and are

established by experiment, and they use systematic concept-based problem-solving approaches that are applicable to a wide variety of situations. Most people (“novices”) see physics more as isolated pieces of information handed down by some authority and unrelated to the real world. To novices,

“learning” physics simply means memorization of information and of problem-solving recipes that apply to highly specific situations.²

Research on traditional instruction

We now examine how well traditional instruction does at getting the average student to think like an expert. Traditional science instruction is used in the overwhelming majority of college physics courses and has familiar characteristics. Most of the class time involves the teacher lecturing to students; assignments are typically back-of-the-chapter-type homework problems with short quantitative answers, and grades are largely based on exams containing similar problems. Over the past couple of decades, physics education researchers have studied the effectiveness of such practices. (For reviews with useful citations, see references 3–5 and the article by Edward Redish and Richard Steinberg, *PHYSICS TODAY*, January 1999, page 24). In this section, we present representative examples of research on three quite different but important aspects of learning: conceptual understanding, transfer of information, and basic beliefs about physics.

The first aspect of learning, conceptual understanding, has been extensively studied^{3,4} and is particularly relevant because the great strength of physics is that a few fundamental concepts can explain a vast range of phenomena. Most studies have looked at students' learning of basic physics concepts in traditional introductory physics courses. The results are remarkably consistent. We will discuss two examples, one from mechanics and one from electricity.

Physics education researchers have developed several carefully constructed tests that explore student understanding of the basic concepts of force and motion. These tests have been administered at the beginning and end of many, many courses across the country. The oldest and best-known test is the Force Concepts Inventory (FCI).⁶ Figure 1 shows a sample question from the FCI and results compiled by Richard Hake from data on 62 courses (14 traditional).⁷ As shown in the figure, students receiving traditional instruction master, on average, less than 30% of the concepts that they did not already know at the start of the class. The result is largely independent of lecturer quality, class size, or institution.

Eric Mazur, a highly renowned teacher at Harvard University, has studied students' understanding of concepts in electricity. Motivated by FCI results, Mazur gave his students an exam with a series of paired problems⁸ such

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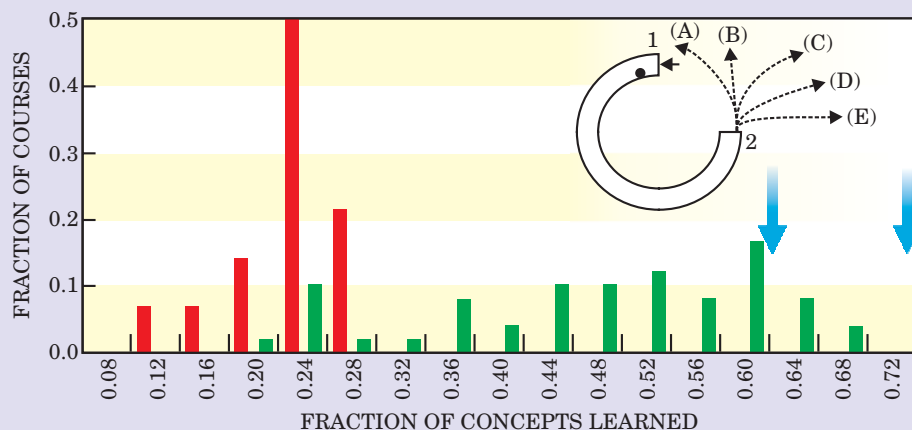


Figure 1. Students master relatively few concepts in physics courses using traditional instruction. The histogram shows, for the Force Concepts Inventory (FCI), the average normalized learning gain—that is, the fraction of the concepts that students learned that they did not already know at the start of the course. Results from 14 traditional courses are in red, and results from 48 courses using a wide variety of interactive-engagement techniques are shown in green. Superimposed on the histogram are data (blue arrows) from two large lecture courses that use well-tested research-based practices.¹⁶ The inset shows a figure accompanying a typical FCI question: Students are asked which path the ball will follow upon exiting the tube. (Adapted from ref. 7.)

as those shown in figure 2. His and similar data show that students are able to correctly answer traditional test questions and complete traditional courses without understanding the basic physics concepts or learning the useful concept-based problem-solving approaches of physicists.

We next examine a second aspect of learning, simple transfer of information and ideas from teacher to student in a traditional physics lecture. The following example is from data collected in our own introductory physics class for non-science majors. After explaining the physics of sound in our usual incredibly engaging and lucid fashion, we brought a violin into class. We explained how, in accordance with the physics we had just explained, the strings do not move enough air to create the sound from the violin. Rather, the strings cause the back of the violin to move via the soundpost, and thus it is the back of the violin that actually produces the sound that is heard. Fifteen minutes later, we asked the students the multiple choice question shown in figure 3, “The sound you hear from a violin is produced mostly by . . .” As illustrated in the figure, only 10% gave the correct answer. We have seen that this 10% level of retention after 15 minutes is typical for a nonobvious or counterintuitive fact that is presented in a lecture, even when the audience is primarily physics faculty and graduate students.

When we have asked physics teachers to predict the student responses to the violin question, nearly all of them greatly overestimate the fraction of students who answer correctly. Many physics faculty go so far as to simply refuse to believe the data. For readers who may share their skepticism, we briefly mention two other studies. Redish had students interviewed just as they came out of his lecture.⁴ The interviewer simply asked the students, “What was the lecture about?” The students were unable to recall anything beyond the general topic. In a more structured study,⁹ Zdeslav Hrepic and coworkers gave 18 students six elementary questions on the physics of sound. Immediately after attempting to answer the questions, the students were told that they were to get the answers to the six questions from watching a 14-minute commercially produced videotaped presentation given by a nationally renowned physics lecturer. For most of the six questions, no more than one student was able to learn the correct answer from the lecture, even under these highly optimized conditions!

When presented with these data, teachers often ask, “Does this mean that all lectures are bad?” The brief answer is no, but to be effective, lectures must be carefully designed according to established, but not widely recog-

nized, cognitive principles about how people learn.¹⁰

Our third topic is research on students’ general beliefs about physics and problem solving in physics. Research groups including our own have studied these beliefs through extensive interviews and well-tested surveys.¹¹ These surveys measure where students’ thinking lies on the expert–novice scale discussed above, and how their views are changed by taking a physics course. The surveys have now been given to many thousands of students at the beginning and end of introductory physics courses at many different institutions. After instruction, students, on average, are found to be less expert-like in their thinking than before. They see physics as less connected to the real world, less interesting, and more as something to be memorized without understanding. This is true in almost all courses, including those with teaching practices that have substantially improved conceptual mastery. If it is any consolation to physics teachers, we have measured similar results from introductory chemistry courses.

The examples we have discussed are just a few from a large body of research on the effectiveness of the traditional approach to teaching physics. The definitive conclusion is that no matter how “good” the teacher, typical students in a traditionally taught course are learning by rote, memorizing facts and recipes for problem solving; they are not gaining a true understanding. Equally unfortunate is that in spite of the best efforts of teachers, typical students are also learning that physics is boring and irrelevant to understanding the world around them.

A better approach

Is there a way to teach physics that does not produce such dismal results for the typical student? Our answer, and that of many others doing research in physics education, is unequivocally yes. Many of the same methods that have worked so well for advancing physics research also improve physics education. These methods include basing teaching practices and principles on research and data rather than on tradition or anecdote; using new technology tools effectively; and disseminating and copying proven results. Considerable evidence shows that this approach works. Classes using research-based teaching practices have shown dramatic increases in retention of information, doubling of scores on the FCI and other conceptual tests, and elimination of negative shifts in beliefs about physics.

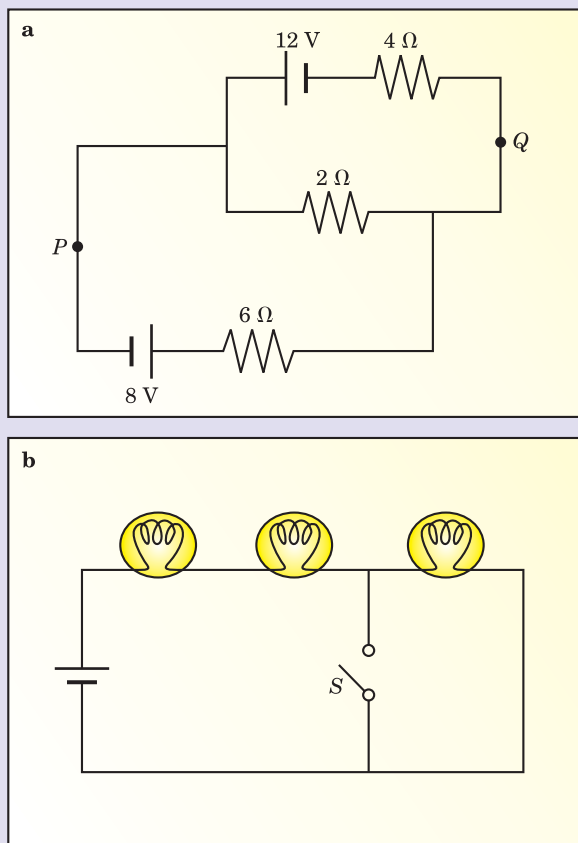


Figure 2. Paired problems compare students' ability to calculate quantitative answers with their conceptual understanding. (a) Students were asked, "For the circuit shown, calculate (a) the current in the 2-Ω resistor and (b) the potential difference between points P and Q." The average score of 69% on the question indicates that most of them were able to calculate the currents and voltages in this moderately complex DC circuit. (b) Those same students performed much worse (average score of 49%) when asked to explain what happens qualitatively to, for instance, the brightness of these light bulbs and the current drawn from the battery when you close the switch S—questions that seem far simpler to any physicist. The message is that students can answer traditional test questions without really understanding basic physics concepts or mastering concept-based problem-solving approaches. (Adapted from ref. 8, with permission of the publisher.)

Research on learning has provided results that both explain many of the disappointing results of traditional instruction and provide guidance as to how to improve. We present three examples here, chosen in part because they are relatively easy to use throughout the standard curriculum and classroom setting. Numerous other examples, including many about specific physics topics, are given in references 3–5.

Cognitive research shows that the amount of new material presented in a typical class is far more than a typical person can process or learn. People's brains function in a way somewhat analogous to a personal computer with very limited random-access memory. The more things the brain is given to process at the same time—the cognitive

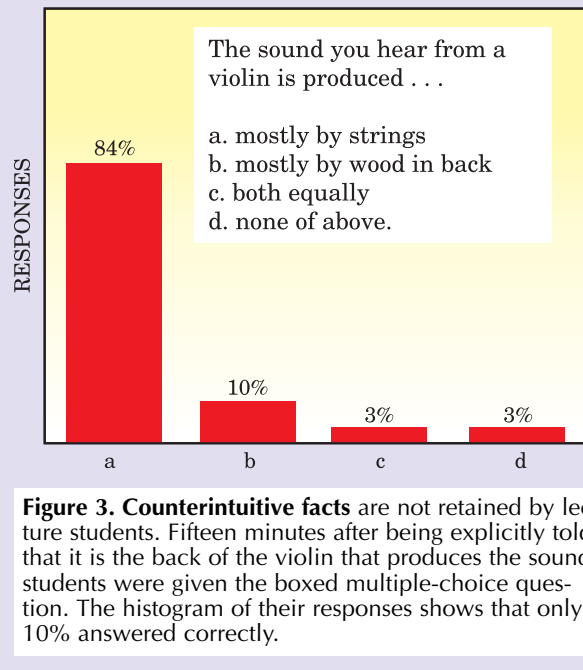


Figure 3. Counterintuitive facts are not retained by lecture students. Fifteen minutes after being explicitly told that it is the back of the violin that produces the sound, students were given the boxed multiple-choice question. The histogram of their responses shows that only 10% answered correctly.

load—the less effectively it can process anything¹² (see figure 4). Any additional cognitive load, no matter what form it takes, will limit people's abilities to mentally process and learn new ideas. This is one of the most well-established and widely violated principles in education, including by many education researchers in their presentations.

Cognitive load has important implications for both classroom teaching and technical talks. To maximize learning, instructors must minimize cognitive load by limiting the amount of material presented, having a clear organizational structure to the presentation, linking new material to ideas that the audience already knows, and avoiding unfamiliar technical terminology and interesting little digressions.

Expert competence^{5,12} is a primary goal of education and is another area in which research has provided useful insights. Expert competence has been found to have roughly two parts: factual knowledge and an organizational structure that allows the expert to effectively retrieve and apply those facts. Organizing physics ideas around general concepts is part of building such a structure. If students do not have a suitable organizational structure, simply pouring additional facts on them may actually deter learning.

To move a student toward expert competence, the instructor must focus on the development of the student's mental organizational structure by addressing the "why" and not just the "what" of the subject. These mental structures are a new element of a student's thinking. As such, they must be constructed on the foundation of students' prior thinking and experience.^{5,12} This prior thinking may be wrong or incorrectly applied, and hence must be explicitly examined and adequately addressed before further progress is possible. The physics education research literature can help instructors recognize and deal with particular widespread and deeply ingrained misconceptions.^{3,4} In summary, expert competence is likely to develop only if the student is actively thinking and the instructor can suitably monitor and guide that thinking.

Our final example of useful research concerns students' beliefs. Students' beliefs about physics and how it is

learned are important.^{1,11} They affect motivation, approaches to learning and problem solving, and, not surprisingly, choice of major. As we noted earlier, teaching practices influence students' beliefs, usually by making them more novice-like. Presenting mechanics in terms of general concepts and the motion of abstract items such as blocks on frictionless ramps can inadvertently teach many students that these principles do not apply to real-world objects. Assigning problems that are graded strictly on a final number, or that can be done by plugging the correct numbers into a given procedure or formula, can teach students that solving physics problems is only about memorization and coming up with a correct number—reasoning and seeing if the answer makes sense are irrelevant. The good news is that courses with rather modest changes to explicitly address student beliefs have avoided the usual negative shifts.¹¹ Those changes include introducing the physics ideas in terms of real-world situations or devices with which the students are familiar; recasting homework and exam problems into a form in which the answer is of some obvious utility rather than an abstract number; and making reasoning, sense-making, and reflecting explicit parts of in-class activities, homework, and exams.

New educational technology

Utilizing principles established by educational research can greatly improve physics education. Technology can make it easier to incorporate these principles into instruction. For example, online surveys and student-faculty e-mail are rather simple ways to enhance communication, thereby helping faculty understand and better guide student thinking. Here we will discuss a couple of more novel technologies—personal electronic response systems and interactive simulations. These technologies are relatively simple and inexpensive, and we have found them to be pedagogically powerful and easy to incorporate into the standard curriculum.

A variety of commercial vendors sell personal electronic response systems, or “clickers” as they're usually known to our students. The various systems are all based on a similar idea. Each student owns a clicker and uses it to answer multiple-choice questions asked during class. A computer records each student's answer. After all the responses are in, the system displays the answers in a histogram like that given in figure 3. Software grades the responses and allows the instructor to later examine each student's answer. A clicker system for a classroom of about 200 seats requires several receivers, a computer, and a projector; the total cost is about \$5000.

If used properly, clickers can have a profound impact on the students' educational experience. The value of the clicker is that it provides a way to quickly get an answer for which the student is accountable, and that answer is anonymous to the student's peers. While the clickers provide some measure of what students are thinking, it is the specifics of the implementation—the change in the classroom dynamic, the questions posed, and how they are followed up—that determines the learning experience. These specifics need to be guided by an understanding of how people learn. Instructors must also make sure their students understand how and why the clickers are being used. If students perceive clickers merely as a way to give more tests, rather than as a method to improve engagement and communication, the clickers will be resented.

We have found that the biggest impact of clickers comes when they are used with a combination of practices that others have developed. We randomly assign students to groups the first day of class (typically three or four students in adjacent seats). Each lecture is designed around

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

Figure 4. Students in lecture are apt to suffer from cognitive overload.

a series of about six clicker questions that cover the key learning goals for that day. Although multiple-choice questions may seem limiting, they can be surprisingly good at generating the desired student engagement and guiding student thinking. They work particularly well if the possible answers embody common confusions or difficult ideas. Useful clicker questions and valuable guidance on writing effective questions are now available.^{8,13}

It is important to actively encourage students to talk to each other about the questions. We do this, sometimes after they have answered individually, by requiring our groups to come to a consensus answer, enter it with their clickers, and be prepared to offer reasons for their choice. Those peer discussions are the times when most students are doing the primary processing of new ideas and problem-solving approaches. Critiquing each other's ideas to arrive at a consensus answer also enormously improves their ability to carry on scientific discourse. Finally, the discussion helps them to learn to evaluate and test their own understanding. Experts have the ability to monitor and test their own thinking on an ongoing basis by asking questions like “Does this make sense?” and “How can I test this?” However, it is very difficult for students to learn this skill without some amount of social interaction and feedback. The student discussions in our classes are inspired by the peer instruction technique popularized by Mazur.⁸ The clickers and consensus groups just provide a way to enhance the process, particularly for the less active or less assertive students.

A major value of clickers is how they can enhance communication in the classroom. The sometimes painful feedback provided to the instructor by histograms like figure 3 is the most obvious. However, there are other, more valuable

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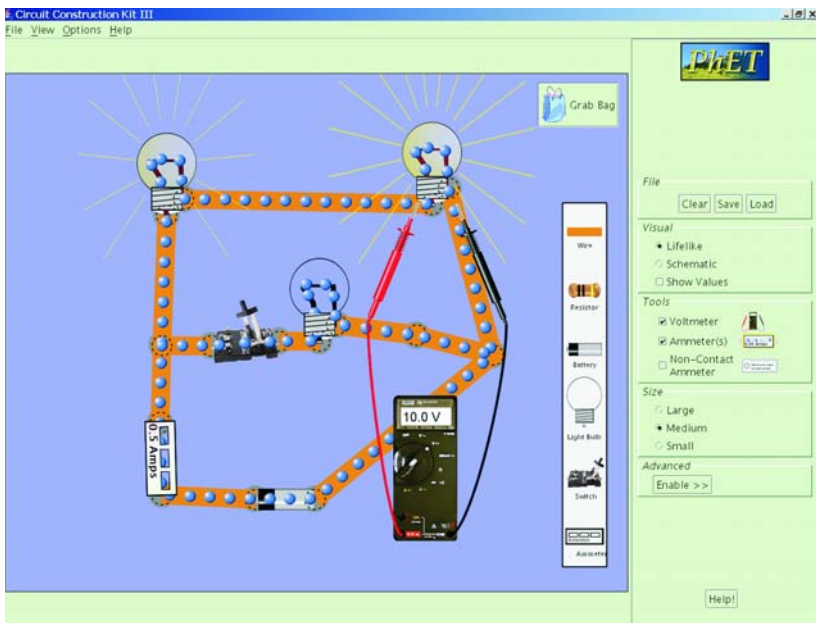


Figure 5. The circuit construction kit is a simulation that allows students to build virtual circuits containing a number of different elements. A pedagogically useful feature of the simulation is that it displays motion of the electrons, shown here in blue. Students who work with the interactive simulation are better able to understand and build real-life circuits. The simulation and many others are available at the Physics Education Technology website, ref. 14.

forms of feedback. By circulating through the classroom and literally listening in on the consensus-group discussions, the instructor can quickly learn particular points of student understanding and confusion. Then in the follow-up lecture or whole-class discussion, the instructor can directly target those specific items of confusion. Perhaps even more important than the feedback to the instructor is the feedback provided to the students through the histograms and peer discussions. Students become much more invested in their own learning. One manifestation of this change is that we now receive many more substantive questions, and they are asked by a much broader distribution of students; 10–15 questions per class period is typical.

Clickers can also be useful in other ways. For instance, we use them to quickly survey the range of student backgrounds and to quiz students at the start of class to check that they've done the assigned reading. Ensuring background reading considerably facilitates useful in-class discussions.

The reality of virtual physics

Interactive simulations that run through a regular Web browser can be highly effective. Using an existing simulation also often takes less preparation time than more traditional materials. Our research group has created and studied the effectiveness of about 45 simulations.¹⁴ We have explored their use in lectures, as part of homework problems, and as laboratory replacements or enhancements. Figure 5 shows our circuit construction kit simulation. This simulation allows one to build arbitrary circuits involving lifelike resistors, light bulbs, wires, batteries, and switches; measure voltages and currents with realistic meters; and see light bulbs lighting up. It

also shows what cannot normally be seen—electrons that flow around the circuit with their velocity proportional to current, immediately responding to any changes in circuit parameters. Our studies¹⁴ have found this simulation helps students understand the basic concepts of electric current and voltage and, when substituted for an equivalent lab with real components, improves how well students can build and explain real-life circuits.

Many physicists find it quite mysterious and somewhat disturbing that carefully developed simulations are more educationally effective than real hardware. Both the efficacy of simulations and the physicists' discomfort can be understood by recognizing the difference between how the beginning student and the expert instructor perceive the same situation. These perceptual differences are readily apparent in our testing of simulations and in other research on the effectiveness of lecture demonstrations.¹⁵

A real-life demonstration or lab includes enormous amounts of peripheral information that the expert instructor filters out without even thinking about it. The student has not learned what can be filtered out, and so all this other information produces confusion and a much heavier cognitive load. The student's attention is often on things the instructor doesn't even notice, because they are irrelevant. For example, in a real circuits lab, inexperienced students will often spend considerable time and concern on the significance of the different colors of the plastic insulation on the wires.

A carefully designed computer simulation can maintain connections to real life but make the student's perception of what is happening match those of experts. This is done by enhancing certain features, hiding others, adjusting time scales, and so on, until the desired student perception is achieved. Simulations also can provide visual representations that explicitly show the models that experts use to understand phenomena that are not directly visible, such as the motion of electrons. It is likely that both features are important in explaining the observed benefits of simulations.

The educational importance of recognizing and dealing with differences between student and expert thinking goes well beyond the use of simulations. An apt metaphor is that of the student and the expert instructor separated by the mental equivalent of a canyon; the function of teaching is to guide the student along the path that leads safely and effectively across the canyon to the nirvana of expert-like thinking. Guidance that ignores the student's starting point or that is interpreted differently than intended usually just sends the student over a cliff. But education research, careful measurement, and new technology make it possible to guide most students safely along the path toward a true understanding and appreciation of physics.

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