

SCIENCE EDUCATION in the 21ST CENTURY Using the Tools of Science to Teach Science

The purpose of science education is not simply to produce the next generation of scientists. Today we all face issues on a global scale that are fundamentally technical—climate change, energy resources, food production, genetic modification, and so on—and as such demand basic scientific literacy throughout our population so that wise decisions can be reached about how to address them. Carl Wieman, Nobel Prize winner in physics in 2001, is director of the Carl Wieman Science Education Initiative at the University of British Columbia. He also retains an appointment to head the science education initiative he founded at the University of Colorado, Boulder, where he serves as Distinguished Professor of Physics. Wieman describes a new approach to teaching science based on advances in the cognitive and neurosciences, rigorous assessment data, and research about how students think about the science disciplines. He outlines the failings of traditional educational practices and suggests specific, data-driven ways to improve teaching and learning in the sciences, noting that such efforts likely would be applicable to some degree across other disciplines.

NOTEBOOK

- We physicists believe that one of the great strengths of physics is that it has a few fundamental concepts that can be applied very widely. This has inspired physics education researchers to study how well students are actually learning the basic concepts in their physics courses, particularly at the introductory level.
- Research vividly documents the failures of traditional methods and the superiority of some new approaches for student learning. But the budget for R&D and the implementation of improved educational methods at most universities is essentially zero.
- Much of educational and cognitive research can be reduced to this basic principle: People learn by creating their own understanding. Effective teaching facilitates that creation by engaging students in thinking deeply about the subject at an appropriate level and then monitoring that thinking and guiding it to be more expert-like.
- Higher education's leaders can cultivate the political will to implement more effective pedagogical approaches to benefit every student in every college and university classroom.



Research in Learning

We need to make science education effective and relevant for a large and necessarily more diverse fraction of the population. To do so, we need to transform how students think so that they can understand and use science like scientists do. But is this kind of transformation really possible for a large fraction of the total population? The hypothesis that I and others have advanced is that it is possible, but only if we approach the teaching of science like a science.

I have conducted an extensive research program in atomic physics for many years that has involved many graduate students, on whose professional development I have spent much time and thought. Over the years I became aware of a consistent pattern: New graduate students would come to work in my laboratory after 17 years of extraordinary success in classes, but when they were given research projects to work on they were clueless about how to proceed. Or worse—often it seemed that they didn't even really understand what physics *was*.

But then an amazing thing would happen. After just a few years of working in the research lab, interacting with faculty and other students, they were transformed. Suddenly they were expert physicists, genuine colleagues. If this had happened only once or twice it would have seemed just an oddity, but it was a consistent pattern. I was puzzled and so I decided to try to figure it out by studying the research on how people learn—particularly how they learn science.

In a traditional science class, the teacher stands at the front of the class lecturing to a largely passive group of students. Those students then go off and do back-of-the-chapter homework problems from the textbook and take exams that are similar to those exercises. Much research has been conducted on this pedagogical strategy; while the data discussed here were gathered mostly in introductory college physics courses, the results are consistent with those of similar studies done in other scientific disciplines and at other grade levels. The results are also consistent with what we know about cognition.

Retaining Information

Lectures were created as a means of transferring information from one person to many, so an obvious topic for research is the retention of that information by the many. The results of two studies are typical and instructive. In the first, Zdeslav Hrepic, N. Sanjay Rebello, and Dean Zollman at Kansas State University (http://web.phys.ksu.edu/papers/2006/Hrepic_comparing.pdf) asked 18 students from an introductory physics class to attempt to answer six questions on the physics of sound and then, primed by that experience, to get the answers to those questions by listening to a 14-minute, highly polished

commercial videotaped lecture given by someone who is supposed to be the world's most accomplished physics lecturer. On most of the six questions, no more than one student was able to correctly get the answer from the lecture.

Taking another approach, a number of times Kathy Perkins and I have presented some nonobvious fact in a lecture along with an illustration and then quizzed the students 15 minutes later on that fact. About 10% remember it at that point. To see whether we simply had mentally deficient students, I once repeated this experiment when I was giving a departmental colloquium at one of the leading physics departments in the United States. The audience was made up of physics faculty members and graduate students, but the result was about the same—around 10%.

Given that thousands of traditional science lectures are being given every day, these results are quite disturbing. Further, based on one of the most well-established, yet widely ignored, results of cognitive science research—that is, the extremely limited capacity of the short-term working memory—these results are likely to be generic. Research tells us that the human brain can hold a maximum of about seven different items in its short-term working memory and can process no more than about four ideas at once. But the number of new items that students are expected to remember and process in the typical hour-long science lecture is vastly greater than seven. We should not be surprised to find that students are able to take away only a small fraction of what is presented to them in that format.

Understanding Basic Concepts

We physicists believe that one of the great strengths of physics is that it has a few fundamental concepts that can be applied very widely. This has inspired physics education researchers to study how well students are actually learning the basic concepts in their physics courses, particularly at the introductory level. Probably the oldest and most widely used assessment tool is the Force Concepts Inventory (FCI) (Hestenes, 1992). This excellent instrument tests students' mastery of the basic concepts of force and motion, which are covered in every first-semester postsecondary physics course. It requires students to apply the concepts of force and motion in a real-world context, such as explaining what happens when a car runs into a truck. The FCI—now administered in hundreds of courses annually—normally is given at the beginning and end of the semester to see how much students have learned during the course.

Richard Hake (1998) compiled the FCI results from 14 different traditional lecture-based courses and found that students mastered no more than 30% of the key concepts that they didn't already know at the start of the course. Similar

sub-30% gains are seen in many other unpublished studies and are largely independent of lecturer quality, class size, and institution. The consistency of those results clearly demonstrates that the problem is in the basic pedagogical approach: The traditional lecture is simply not successful in helping most students achieve mastery of fundamental concepts. Pedagogical approaches involving more interactive engagement of students show consistently higher gains on the FCI and similar tests.

Affecting Beliefs

Students believe certain things about what physics is and how one goes about learning the discipline, as well as how one solves problems in physics. Beliefs about physics lie on a spectrum that ranges from “novice” to “expert.” My research group and others have developed survey instruments that can measure where on this scale a person’s beliefs lie.

One would expect that students would begin their college physics course somewhere on the novice side of the scale and that after completing the course they would have become at least somewhat more expert-like in their beliefs. The data, however, show just the opposite. On average, students have more novice-like beliefs *after* they have completed an introductory physics course than they had when they started; this result was found for nearly every such course measured. Further, research shows that the effect of introductory college chemistry courses is if anything even worse.

Research on learning sheds light on this distressing result. Cognitive scientists have identified a few basic components that constitute expert competence in any discipline. The first is that experts have extensive factual knowledge about their subject, which is hardly a surprise. But in addition, they have a mental organizational structure that facilitates the retrieval and effective application of their knowledge. Third, experts have an ability to monitor their own thinking (“metacognition”), at least in their discipline of expertise. That is, they are able to ask themselves, “Do I understand this? How can I check my understanding?”

Traditional science instruction concentrates on teaching factual knowledge, with the implicit assumption that expert-like ways of thinking about the subject come along naturally or are already present. But that is not what cognitive science tells us. Rather, students need to develop expert ways of thinking by means of extended, focused mental effort. Further, new ways of thinking are always built on the prior thinking of the individual; thus, if the educational process is to be successful, it is essential that prior thinking be taken into account.

Basic biology tells us that everything that constitutes “understanding” science and “thinking scientifically” resides in the long-term memory, which is developed via the construction

and assembly of component proteins. A person who does not go through this extended mental construction process simply cannot achieve mastery of a subject.

Improving Teaching and Learning

Thinking back to the graduate students for whom the first 17 years of education seemed so ineffective, while a few years of doing research turned them into expert physicists, it is clear that their traditional science courses did little to develop expert-like thinking about physics. But why is working in a research lab so different?

Much of educational and cognitive research can be reduced to this basic principle: People learn by creating their own understanding. That does not mean, however, that they must or even can do so without assistance. Effective teaching facilitates that creation by engaging students in thinking deeply about the subject at an appropriate level and then monitoring that thinking and guiding it to be more expert-like. That is precisely what occurs with graduate students working in a lab, focusing intently on solving real physics problems. After a few years in that environment they turn into experts, not because there is something magic in the air in the research lab but because they are engaged in exactly the cognitive processes required for developing expert competence.

It would be quite effective to put every student, including undergraduates, into a research lab to work one-on-one with a faculty member rather than taking classes, but obviously that is not practical as a widespread solution. Economic realities dictate that we have to use courses and classrooms, so the question is, how can we use these ideas to improve classroom teaching? The key is to incorporate desirable cognitive activities, as revealed by research, into normal course activities.

A significant community of science education researchers, particularly in physics, is taking this approach to the development and testing of new pedagogical methods. These efforts are paying off in clear demonstrations of improved learning. Indeed, some innovative pedagogical strategies are sufficiently mature that they are being routinely replicated by other instructors with similar results.

Perhaps the most straightforward way to improve learning recognizes the limited capacity of the short-term working memory and so reduces cognitive load. Some ways to do so are obvious, such as slowing down. Others include having a clear, logical, explicit organization to the class (including making connections between different ideas presented and connections to things the students already know); using figures where appropriate rather than relying only on verbal descriptions; and minimizing the use of technical jargon. These strategies reduce

unnecessary cognitive demands and result in more learning.

Other strategies to improve learning recognize the influence of student beliefs about science and how those beliefs affect their interest in the material and, likewise, their retention of content. Specific interventions as straightforward as explaining how a topic operates in the real world and showing how it connects to something the student already knows have been shown to prevent decline along the spectrum of beliefs toward more novice-like. Further, a variety of technological approaches have also been shown to be quite effective at facilitating desired learning and extending instructors' abilities to engage and guide far more students at once than is possible in a typical lecture course. For example, my research group has created and tested more than 60 online interactive simulations and made them available for free at <http://phet.colorado.edu>.

Institutional Change

We now have good data showing that traditional approaches to teaching science are not successful for a large proportion of our students, and we have a few research-based approaches that achieve much better learning. The scientific approach to science teaching works, but how do we make this the norm for every teacher in every classroom, rather than just a set of experimental projects?

I believe change must first occur at major research universities, because those institutions set the norms that pervade the education system regarding how science is taught and what it means to "learn" science. Moreover, their departments produce most of the college teachers who then go on to teach science to the majority of college students, including future school teachers. Although I am reluctant to offer simple solutions for such a complex problem, perhaps the most effective first step will be to provide sufficient carrots and sticks to convince faculty within each department or program to come to a consensus as to their desired learning outcomes at each level (course, program, etc.) and to create rigorous means to measure the actual outcomes. These learning outcomes cannot be vague generalities but rather must be specific things they want students to be able to do that demonstrate the desired capabilities and mastery, and hence can be measured in a relatively straightforward fashion. Methods and instruments for assessing the outcomes must meet certain objective standards of rigor and also be collectively agreed upon and used in a consistent manner, as is done in scientific research.

Several obstacles hinder change in the current system. First, the current connection between the incentives in the system and student learning is weak at best. Many believe this is so because

research universities and their faculty don't care about teaching or student learning. I disagree—most instructors do indeed care a great deal about student learning. The real problem is that we have almost no authentic assessments of what students actually learn, so it is impossible to broadly measure that learning and likewise impossible to connect it to resources and incentives.

The second obstacle to change is that while we know how to develop the necessary tools for assessing student learning in a practical, widespread way at the university level, carrying this out would require a significant investment. Introducing effective research-based teaching in all college science courses—by, for instance, developing and testing pedagogically effective materials, supporting technology, and providing for faculty development—would also require resources. But the budget for R&D and the implementation of improved educational methods at most universities is essentially zero. More generally, the political will on campus to bring about cultural change along these lines is absent.

Conclusion

Our society faces both a demand for improved science education and exciting opportunities for meeting that demand. Adopting a more scholarly approach to education—that is, utilizing research on how the brain learns, carrying out careful research on what students are learning, and adjusting our instructional practices accordingly—has great promise. Research vividly documents the failures of traditional methods and the superiority of some new approaches for student learning. The challenge is to develop a mindset that teaching should be pursued with the same rigorous standards of scholarship as scientific research. Higher education's leaders can help make that happen by cultivating the political will to implement more effective pedagogical approaches to benefit every student in every college and university classroom.

References

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NOTE: This summary is based on Carl Wieman's presentation at the Forum's 2007 Aspen Symposium and on prior remarks published in the Sept./Oct. 2007 issue of Change.

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