GRAND CHALLENGE: UNDERGRADUATE TEACHING

Transformation Is Possible If a University Really Cares

The same attention to scientific detail that led to his Nobel Prize is helping Carl Wieman improve how undergraduates learn science

The way that most research universities across North America teach science to undergraduates is worse than ineffective, says Carl Wieman. It's unscientific.

A Nobel Prize–winning physicist turned science educator, Wieman doesn't understand why institutions of higher education would disregard decades of research showing the superiority of student-centered, active learning over the traditional 50-minute lecture. Using that outdated approach, he says, means universities are squandering talent at a time when U.S. higher education is being criticized for not turning out enough science-savvy graduates to keep the country competitive.

Wieman has spent the past 15 years applying the science of learning to how undergraduate science courses are taught. First at the University of Colorado, Boulder, (colorado.edu/sei) and, more recently, at the University of British Columbia (UBC), Vancouver, in Canada (cwsei.ubc.ca), Wieman and his colleagues have made impressive strides in changing how individual faculty members teach. Those changes, within individual courses, have translated into big improvements in student learning.

Those courses are offered by academic departments, which are his real target. Departments define the reward structure

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Engaged instruction. Carl Wieman uses active learning tools to teach an undergraduate course at the University of Colorado in 2001.

for faculty members through their authority to hire, promote, and grant tenure, he says. So the best way to sustain improvements in teaching and learning is to get departments to buy into the need to change the courses that they offer. And that's begun to happen at UBC, one of Canada's elite universities.

Wieman's passion for the subject, combined with his stature as a Nobelist, has focused national attention on the high attrition rate among students who declare an interest in earning a degree in a STEM (science, technology, engineering, and mathematics) field. It's one of the biggest impediments to any effort to train more scientists and engineers. "I think Carl, more than anybody else, put a spotlight on the need to improve undergraduate education," says Subra Suresh, who last month stepped down as director of the National Science Foundation (NSF). "It wasn't a surprise to universities, but his work has highlighted the problem."

Colleagues also laud Wieman's rigorous approach to reform. "I have an incredible amount of respect for his deep commitment to the evidence," says Susan Singer, head of undergraduate education at NSF and a national leader in reforming undergraduate biology education. "Carl is someone who digs in and really wants to know."

Notwithstanding his success at Colorado and UBC, Wieman has made much less progress toward another of his goals: overturning an academic culture that values research over teaching. Working in the White House Office of Science and Technology Policy (OSTP) as associate director for science, Wieman was the de facto science education czar for the Obama administration. But his 20 months on the job taught him just how hard it is to change prevailing attitudes within U.S. higher education.

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While at OSTP, Wieman floated the idea of requiring universities to collect and disseminate information on their teaching practices to remain eligible for federal research dollars. The policy would be a stick to get universities to pay more attention to teaching, he reasoned.

"There's an entire industry devoted to measuring how important my research is, with impact factors of papers and so on," Wieman says. "Yet, we don't even collect data on how I am teaching. It receives no attention. … If everything about teaching remains hidden, then universities can avoid having to devote anything more than minimal effort to doing it well. They can instead spend most of their time and money on research."

Wieman pushed the idea at numerous meetings with other government science officials and academic leaders. But they recoiled in horror at the prospect of what they viewed as another unfunded federal mandate. They prefer a 5-year effort begun last year by the 62-member Association of American Universities that aims to create a voluntary "framework" for improving teaching practices that institutions can adapt to their own situation and implement at their own pace.

"I'm very supportive of improving undergraduate STEM teaching," says Francis Collins, director of the National Institutes of Health (NIH), which spends more money on academic research than any other federal agency. "But this struck people as the wrong pathway by which to achieve the desired outcome, and not very fair."

As if taking on the nation's research establishment wasn't enough of a challenge, last June, Wieman received a sudden diagnosis of multiple myeloma. To deal with this health crisis, he abruptly resigned from his White House post and enrolled in a clinical trial at NIH using two experimental drugs. That treatment ended in January, and the 62-year-old Wieman says he's "happy and healthy."

Online
sciencemag.org
Podcast interview with author Jeffrey Mervis (http://scim.ag/pod_6130).

Wieman, who is leaving UBC but declined to say where he's going, has returned to the lecture circuit with an updated version of his standard talk, entitled "Taking a Scientific Approach to Science and Engineering Education." He's definitely not cowed by the prospect of taking a long, hard road toward his goal. In fact, his personal metric for any reform worth attempting is its ability "to generate significant opposition." Speaking at a session of the February annual meeting of AAAS (which publishes *Science*) in Boston, Wieman said that transforming undergraduate teaching "passes that litmus test."

Giving reform a chance

Wieman's personality and upbringing seem well-suited to a grand challenge like remaking undergraduate science education. Before deciding on a scientific career, he embraced a succession of passions, including chess and tennis, which for a time were all-consuming. "Monomaniacal pretty much describes me," Wieman confessed during a 2007 interview with the Nobel committee. "My view of everything is that you become good at something by focusing and working hard at it." Eventually, he recalls, "science [became] such an activity."

That doggedness served him well in pursuing his Nobel Prize–winning research. In 1925, Albert Einstein, building on the work of Indian physicist Satyendra Nath Bose, deduced that cooling a gas of certain atoms should make all the atoms suddenly flop into the same lowest energy quantum wave. Such a macroscopic matter wave is known as a Bose-Einstein condensate. Some 70 years later, Wieman and Eric Cornell of JILA, a lab run jointly by the National Institute of Standards and Technology and the University of Colorado, Boulder, achieved one by employing magnets and lasers to cool rubidium-87 atoms to within a millionth of a degree of absolute zero. In 2001, the two physicists shared the Nobel Prize in physics with Wolfgang Ketterle of the Massachusetts Institute of Technology in Cambridge, who achieved a similar result with sodium-23 atoms.

Wieman and Cornell at least had the advantage of knowing what a Bose-Einstein condensate would look like before they created one. In contrast, many faculty members might not recognize high-quality, student-centered learning because they may never have experienced it. Wieman admits that many notable scientists have thrived on a diet of traditional teaching practices and that the current rewards system at most universities gives faculty members little reason to try something different.

"I'm certainly not one to dismiss the importance of research," Wieman says. "But people need to recognize how totally dominant the reward system is. There are a lot of faculty who feel, completely appropriately, that 'I could spend more time improving my teaching, but that's not what I'm supposed to be doing.' So you have to figure out a way for them to be able to improve their teaching without making a big sacrifice in their research activities."

Wieman embarked on his quest to improve undergraduate education after pondering his own career as a professor and educator. And like the scientist that he is, he began by asking himself some basic questions. Why, he wondered, did students in his introductory courses do so poorly, and even regress, after he delivered lectures covering what they needed to know? Why couldn't he identify at the outset which graduate students were most likely to succeed? And why did most of them become productive scientists after a few years in his lab?

Digging into the literature on teaching and learning yielded some insights. His graduate students had learned to think like scientists, he realized, by doing real science under the supervision of a world-class scientist. Developing expertise, he came to understand, is a slow and arduous process marked by repeated failures.

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"The apprentice model works pretty well in graduate school because the faculty member can see if the student is learning how to build a laser system, or write a paper, or give a professional talk," says University of Colorado, Boulder, physicist and education researcher Noah Finkelstein, who has worked closely with Wieman and now directs the university's newly formed Center for STEM Learning. "Those are things we actually want them to do. We give them feedback along the way, and we take in feedback from them and adjust our mentoring. But that system is just too costly at the undergraduate level."

Instead, faculty members must interact with hundreds of students in a large hall. Most choose to do that via a lecture. But research has shown that most students cling to their misconceptions even after sitting through a brilliant lecture.

What works better than lectures and homework problems, according to numerous studies, is having students work in small teams with instructors who can help them apply those basic concepts to real-life situations. But what's the best way to implement active, student-centered learning? The answer, Wieman decided, lay in melding it with the concept of deliberate practice.

That idea, developed by psychologist K. Anders Ericsson of Florida State University in Tallahassee, treats the brain as a muscle that must be exercised to perform at its peak. It's how a novice becomes an expert, whether in music, sports, or science. "We have learned that complex expertise is a matter not of filling up an existing brain with knowledge, but of brain development," Wieman says.

Deliberate practice, Wieman wrote in the fall 2012 issue of *Issues in Science and Technology*, "involves the learner solving a set of tasks or problems that are challenging but doable and that involve explicitly practicing the appropriate expert thinking and performance." The teacher, or coach, offers appropriate incentives to encourage students to master the necessary skills, as well as continuous feedback to help them remain on task. As with any sport, he notes, "[t]housands of hours of deliberate practice are typically required to reach an elite level of performance."

The two concepts created an intellectual framework around which to transform undergraduate science. "Just as we have physics principles, here are the principles that work, and they are consistent with what others had done," Wieman says. "It also allows you to go into disciplines where there hadn't been much work done, like oceanography, and make some generalizations. It's very much like science itself."

In a 2011 paper in *Science,* Wieman and his colleagues describe the power of active learning and deliberate practice. The instructor for one section of an introductory physics class for engineers at UBC used these principles, while the other instructor delivered the normal lectures. The first group of students scored more than twice as high on a multiple-choice test of the material covered than did those in the control group.

"The results were so dramatic from this relatively modest experiment that the entire [physics] department had an epiphany," remarks Simon Peacock, UBC's dean of sciences. "It sent them a clear message: Wow, we can actually teach better."

Wieman says that active learning and deliberate practice is now the norm in 99 UBC courses enrolling 31,200 students. Many are introductory courses taken by freshmen and sophomores who are still uncertain of their major field of study. "We have substantially changed more than half of the math and science courses a UBC student in the college of science will take in their first 2 years," Wieman says, citing results from a recent survey of how faculty members have changed their teaching practices since the Carl Wieman Science Education Initiative was launched in 2007.

"We've hit it out of the park with earth and ocean sciences," one of seven departments that are part of the university-funded initiative, Peacock says. "I will declare them to be a success."

Wieman believes that deliberate practice can also help students in primary and secondary school who, for whatever reason, are ill-prepared for success in STEM subjects. His efforts have helped resolve "a huge controversy," says NSF's Singer, over whether the vast majority of students are capable of doing high-level math and science.

"Having Carl stand up and say we should stop doing STEM talent selection and start doing STEM talent development completely changes the nature of the conversation," says Singer, on leave from her post as a biology professor at Carleton College in Northfield, Minnesota. "It's really a question of how you structure the learning environment. And his work has shown that active learning strategies are more effective."

From my way to the right way

What does it take to transform an undergraduate science course? Wieman's approach relies heavily on a cadre of science teaching and learning fellows, who are typically postdocs. At its height, the Colorado initiative employed a dozen such fellows; at UBC, the number peaked at nearly two dozen.

The fellows are trained in the many steps needed to transform a university lecture course—steps that faculty members are unlikely to take on their own, either out of ignorance or because they simply don't have the time to do what's needed. Katherine Perkins, who directs both the science education initiative at Colorado and the related PhET project (phet.colorado.edu), which has created thousands of research-based simulations of physical phenomena, calls the teaching and learning fellows "engines of change."

Meeting for the first time with a faculty member, a fellow might start by asking what the faculty member wants students to know how to do at the end of the course. That's a more useful metric than asking what a student "should understand," explains Beth Simon, director of the Center for Teaching Development at the University of California, San Diego, who spent the 2007 to 2008 academic year at UBC as a fellow in the computer science department before returning to UCSD.

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Once the faculty member articulates the real goals of the course, those skills are converted into learning objectives. The next step is to write up multiple-choice questions aimed at helping students achieve each learning objective. The so-called clicker questions (the name comes from the electronic device that students use to record their answers) usually focus on common student misconceptions about the concepts.

The questions become the basic curriculum for the course. But getting from skills to clicker questions can be difficult. Simon figured that the final exam would provide a useful guide to what students were expected to learn. Instead, instructors would admit that they didn't really know what concepts some test questions were meant to measure, she says, and that other questions covered concepts not central to the course.

Most courses come with only a three- or four-sentence description in the syllabus. That brevity gives whoever is teaching the course a lot of leeway. Some faculty members have been teaching the same course for years, Simon says, and for them, "learning outcomes were a nonstarter. 'I teach 101 my way,' they would say." In contrast, some courses are "owned" by the department and a consensus exists on what students are expected to know regardless of who is teaching the course.

A transformed course typically begins not with a lecture but with a clicker question. Students gather in small groups to discuss it, and a fellow assigned to the course circulates through the classroom to guide the inquiry process. Once the students have punched in their answers, the faculty member might offer a microlecture aimed at correcting their mistakes and filling in gaps in their knowledge. Once the concept is clear, the class moves on to the next clicker question.

Students taking transformed courses are usually more active than in a typical lecture class. Faculty members need to remind students regularly why they will not be lecturing, Simon says, as well as explain the importance of peer instruction. To get the most from the class time, students are assigned outside reading and turn in homework that measures their understanding of the material.

Some students are uncomfortable with this approach—even if it's more effective. "I remember getting an evaluation from one [UCSD] student who had just finished my course," says Simon, a pioneer in the use of peer instruction within her field. "I loved it. It read, 'I just wish she'd have lectured. Instead, I had to learn the material myself.' "

The increased student engagement in a transformed course is music to the ears of the average faculty member. "Most faculty want their students to learn more," says Perkins, whom Wieman hired in 2003 as one of the initiative's first teaching fellows. "They look at the final exam, sigh, and say, 'Why did only 60% get that question right?' " Simon adds, "If they can have more fun, they will choose to use these methods."

A department should plan on spending about 5% of its budget for 5 years to transform its courses, Wieman says. Lesser

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amounts are required to sustain progress, he adds, although new faculty members must be trained and existing faculty members need ongoing support and, occasionally, a sympathetic ear. At Colorado, for example, departments competed for grants of roughly $600,000 to $800,000 each. UBC's $10 million commitment to the initiative allowed Wieman to double the size of departmental awards, and a more recent $2 million donation from David Cheriton, a professor of computer science at Stanford University, is fueling reform within the math and computer science department.

Wieman's campaign to transform departments isn't the only game in town. Finkelstein's new center at Colorado, funded by an NSF planning grant, is supposed to serve as a focal point for some 75 STEM-related activities on campus. And Colorado's Perkins hopes that NSF will put up several million dollars for a Web site to help faculty members use the PhET simulations that she and others have created and to study their impact on teaching and learning.

But money remains tight. Wieman says he can't afford to conduct the rigorous, outside assessments that normally accompany NSF-funded reforms because he feels that institutional funds should redound to the benefit of the institution. However, the dearth of peer-reviewed publications has led some scientists to question what Wieman's Colorado and UBC initiatives have accomplished.

"When people ask what we've done," Finkelstein says, "and I say we've shifted institutional identity and culture, half the time their response is, 'Wow, that's terrific.' But the other half say, 'So all you've done is talk?' "

Wieman himself offers a frank answer when asked whether he expects the UBC reforms to stick. "That's why you do research," he says. "This was a one-time intervention. And people have a right to wonder what will happen next.

"I'm more optimistic than I was a year ago," he adds, "because people who we thought weren't interested are now saying, 'Look, I made this change and I'm thinking of doing more.' But I won't give you good odds that they will still be doing it in 10 years."

Carrot or stick?

In 2010, Wieman decided to come to Washington for the chance to influence undergraduate science education on a national scale. "My top priority at OSTP was to improve undergraduate education," he says. "We know what to do that will help students learn more and be more successful and how to get a broader group of students doing it."

While there, Wieman came up with his simple, market-driven first step: Require universities to compile and release data on their teaching methods as a condition for receiving federal research funds. As students began using the data released by universities to help choose a college, he reasoned, universities would feel compelled to improve their teaching practices in order to attract the best applicants. "If an agency were to require every grantee to provide this information," he says, "then the next year teaching would look completely different because somebody is looking at it."

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Wieman promoted the idea tirelessly in meetings with his government colleagues as well as the presidents of several leading research universities, seeing it as a painless way to propel reform. But they pushed back hard. It's hard to define particular teaching practices, they told Wieman. Self-reported data are unreliable, they added, and collecting such data would be a burden. Last April, the presidents of several prominent universities even wrote a letter to then–White House Chief of Staff Jacob Lew in an attempt to head off Wieman's proposal.

A few months later, Wieman was gone. But he hasn't changed his mind one iota, and he says that none of the community's objections are valid.

For starters, he says, colleagues at UBC and Colorado have created a questionnaire that collects such data and requires only a few hours of effort by an entire department—"a tiny amount compared to what is spent in a single faculty meeting," he snickers. Universities have no incentive to game the system, he adds, because students would soon expose any institution that had submitted bogus information. And he scoffs at the idea that tracking a fundamental purpose of a university could be regarded as a "burden."

Part of their objections, he speculates, is that the data could prove embarrassing. "Educational transparency is a threat to their status," he argues. "Maybe it won't make them look so good."

NIH's Collins says that's not the reason he prefers a voluntary approach. "I know that Carl is skeptical universities will do it on their own," he says. "But I have yet to be convinced that they won't. I don't know that all universities will want to participate. But I think there will be some who would say, 'Yeah, we believe in this. It's the right thing to do.' "

Government officials and university leaders typically defend the value of federally funded research by citing its role as an engine of economic growth. In the case of biomedical research, they also note its potential to save lives. But Wieman doesn't think those arguments really address the growing clamor from the public and politicians for universities to show that an undergraduate education is worth the rising cost of tuition. That skepticism, he says, has also fueled a decadelong assault by many state legislatures on their flagship public universities.

A more effective response, Wieman says, would be for university presidents to emphasize how research can lead to better teaching. "I think the solution is to show that you can really use that research expertise to improve education," he says. "Deliberate practice and other approaches is calling on, and demanding of, the research expertise embodied by that faculty."

"If you pitch that message," he continues, "then suddenly it becomes clear how having a great research university translates into better education for students in my state. Right now it's not worth the investment, because it's not happening. But it could."

–JEFFREY MERVIS