THE SCIENCE OF TEACHING SCIENCE

Active problem-solving confers a deeper understanding of science than does a standard lecture. But some university lecturers are reluctant to change tack.

BY M. MITCHELL WALDROP

Outbreak alert: six students at the Chicago State Polytechnic University in Illinois have been hospitalized with severe vomiting, diarrhoea and stomach pain, as well as wheezing and difficulty in breathing. Some are in a critical condition. And the university's health centre is fielding dozens of calls from students with similar symptoms.

This was the scenario that 17 third- and fourth-year undergraduates dealt with as part of an innovative virology course led by biologist Tammy Tobin at Susquehanna University in Selinsgrove, Pennsylvania. The students took on the role of federal public-health officials, and were tasked with identifying the pathogen, tracking how it spreads and figuring out how to contain and treat it — all by the end of the semester.

Although the Chicago school and the cases were fictitious, says Tobin, "we tried to make it as real as possible". If students decided to run a blood test or genetic assay, Tobin would give them results consistent with enterovirus D68, a real respiratory virus. (To keep the students from just getting the answer from the Internet, she portrayed the virus as an emergent strain with previously unreported symptoms.) If they decided to send a team to Chicago, Tobin would make them look at real flight schedules and confirm that there were enough seats.

ILLUSTRATION BY VASAVA

In the end, the students pinpointed the virus, but they also made mistakes: six people died, for example, in part because the students did not pay enough attention to treatment. However, says Tobin, "that doesn't affect their grade so long as they present what they did, how it worked or didn't work, and how they'd do it differently". What matters is that the students got totally wrapped up in the problem, remembered what they learned and got a handle on a range of disciplines. "We looked at the intersection of politics, sociology, biology, even some economics," she says.

Tobin's approach is just one of a diverse range of methods that have been sweeping through the world's undergraduate science classes. Some are complex, immersive exercises similar to Tobin's. But there are also team-based exercises on smaller problems, as well as simple, carefully tailored questions that students in a crowded lecture hall might respond to through hand-held 'clicker' devices. What the methods share is an outcome confirmed in hundreds of empirical studies: students gain a much deeper understanding of science when they actively grapple with questions than when they passively listen to answers.

"We find up to 20% better grades over usual methods," says Tom Duff, a computer scientist who developed a team-based learning approach at the University of the West of Scotland in Paisley, UK. Other active-learning proponents have found similar gains. Last year, a group led by biologist Scott Freeman at the University of Washington in Seattle published an analysis of 225 studies of active learning in science, technology, engineering and mathematics (STEM) and found that active learning cut course failure rates by around one-third[1].

"At this point it is unethical to teach any other way," declares Clarissa Dirks, a microbiologist at the Evergreen State College in Olympia, Washington, and co-chair of the US National Academies Scientific Teaching Alliance, an initiative to reform undergraduate STEM education.

Active learning is winning support from university administrators, who are facing demands for accountability: students and parents want to know why they should pay soaring tuition rates when so many lectures are now freely available online. It has also earned the attention of foundations, funding agencies and scientific societies, which see it as a way to patch the leaky pipeline for science students. In the United States, which keeps the most detailed statistics on this phenomenon, about 60% of students who enrol in a STEM field switch to a non-STEM field or drop out[2] (see 'A persistence problem'). That figure is roughly 80% for those from minority groups and for women.

TOUGH SELL

Not everyone embraces the idea. Active learning can be a tough sell to faculty members who thrived on standard lectures during their own student years, and who wonder whether the benefits of active learning — which requires substantially more preparation than do standard lectures — could possibility justify the time that the approach would take away from their research.

Understanding and addressing the resistance has become one of the reformers' prime concerns. Robert Lue, the other co-chair of the teaching alliance and director of the Derek Bok Center for Teaching and Learning at Harvard University in Cambridge, Massachusetts, says that he is "hell bent on erasing this sense that research is where you apply your intellect, and teaching is a rote skill". Scientists need to approach teaching with the same rigour and appreciation for evidence that they exercise in the laboratory, he says. "It's at the frontier of research. And the more people we get involved, the faster that research will go."

On the surface, active-learning classes can seem to differ little from more conventional approaches. Undergraduate students have always had discussion sessions to ask about the course material, and laboratory classes in which they would carry out experiments. But if you look more closely, says Tobin, these are often just 'cookbook' exercises. The typical approach is 'read that and be prepared to talk about these questions', or 'follow that procedure and you'll get this result'. In an active-learning class such as hers, she says, the students take charge of their own education. "They are framing the questions themselves."

The same is true for active learning in first-year courses, in which the teachers often do supply the questions — but frame them in a way that asks for more than a rote recitation of facts. It is the difference between

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'name the sensory nerves of the leg', and what neuroscientist Sarah Leupen asks of her introductory physiology class at the University of Maryland, Baltimore County (UMBC):

You're innocently walking down the street when aliens zap away the sensory neurons in your legs. What happens?

a) Your walking movements show no significant change.
b) You can no longer walk.
c) You can walk, but the pace changes.
d) You can walk, but clumsily.

"We usually get lots of vigorous debate on this one," says Leupen, who spends most of her class time firing such questions at her students. "It's lovely to experience."

What makes those questions special is that the students cannot answer them simply by reading the course material — although they are expected to have done that before attending class. Instead, they have to apply what they have learned, which they do by clustering around tables in small teams and arguing over the options. That struggle is the real pay-off, says Leupen, who eventually explains the right answer (in this case, d). And if a team gets it wrong, she says, "that's usually a good thing — because then they really remember it".

Evidence has been accumulating for decades that students who actively engage with course material will end up retaining it for much longer than they would have otherwise, and they will be better able to apply their knowledge broadly. But the evidence began to draw widespread attention only around the turn of the century — not least thanks to Carl Wieman, who suddenly became one of the movement's most visible champions when he was awarded the 2001 Nobel Prize in Physics for his co-discovery of Bose–Einstein condensates. "I started way before the Nobel prize," says Wieman, who is now at Stanford University in California. "It's just that people didn't pay attention to me until then."

Wieman's conversion began in the late 1980s, when he noticed something about the graduate students coming into his atomic-physics lab — then at the University of Colorado Boulder. "They had done really well as undergraduates, but couldn't do research," he says. Over the years, they learned how to be good scientists, "but that had little to do with how well they had done in their courses".

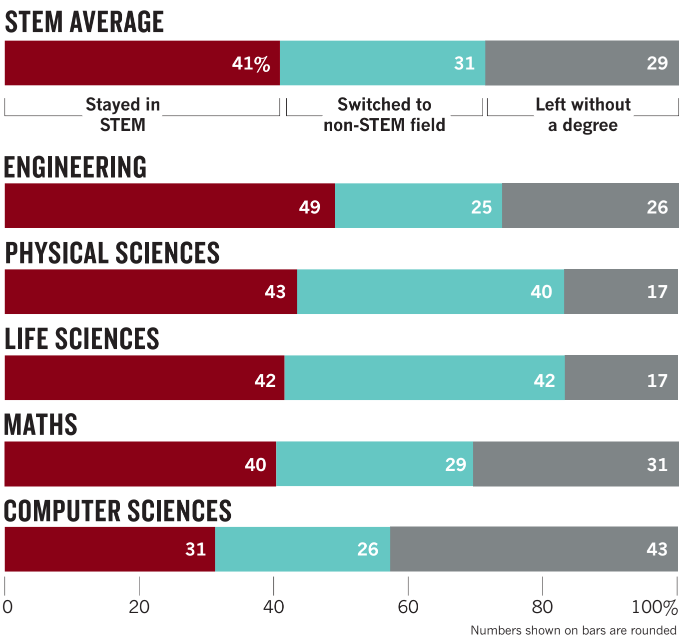
In trying to figure out why, Wieman came across the already huge body of empirical research on learning — most of it totally unknown to science departments. Among the most striking findings, he says, was one[3] that explained his own observation. It showed that in the traditional way of teaching, students could pass the test, but did not get a basic conceptual model of the subject, he says.

Other scientists were coming to much the same realization, and they were starting to experiment with other ways to teach. By the time Wieman's Nobel shone a spotlight on the efforts, many fields had started what is now known as Discipline-Based Education Research: investigations into active methods for teaching concepts specific to each branch of science[4].

Other powerful advocates included biologist Bruce Alberts, then president of the US National Academy of Sciences. In 2004, Alberts consolidated several academy panels into the Board on Science

A PERSISTENCE PROBLEM

A study tracking 17,000 post-secondary students in the United States and Puerto Rico found that only two-fifths of those enrolled in a STEM discipline went on to obtain a degree in the field, or were still studying for one 6 years later.



SOURCE: REF. 2

Education: a group of senior scientists, initially chaired by Wieman, that has gone on to release a series of reports on education reform. The most recent of those, published in January 2015, is essentially a how-to manual for applying active learning in undergraduate settings[5].

CULTURE SHOCK

Yet there is still plenty of scepticism, says Linda Hodges, a biochemist and head of the Faculty Development Center at the UMBC, and author of a forthcoming book on overcoming obstacles to education reform. One big reason, she says, is that for many scientists, active learning is sharply at odds with their beliefs about teaching.

Researchers often feel that a teacher's job is simply to communicate content: the factual knowledge covered in the course. That is a big stumbling block for active learning, because time spent on team discussions and the like can seem like time taken away from that content. Getting past that requires compromise, says Jeff Leips, a geneticist who teaches ecology and evolution at the UMBC. "You have to accept that you can't cover everything to the same level." But the pay-off is that the students retain much more of the material that is covered, and are able to use that knowledge much more effectively.

Another common belief, says Hodges, is that it is the professor who should be in control of the classroom. "A lot of these pedagogies ask you to relinquish some of your control and hand it over to a bunch of novice students," she says. "And that sounds odd to a lot of faculty." It definitely requires a different set of skills, agrees Leips. "A lecture is like a performance: you know the script." But an active-learning class is more like improvisational acting, he says. "You have to go with the flow", responding to questions and situations as they arise. And not everyone is comfortable with that.

Adding to the resistance is that many faculty members who try active learning hastily back off when the techniques do not seem to work, or when students start to turn in teacher evaluations that say, 'I had to teach myself!' or, 'Just tell me what I need to know!'.

One faculty member, who asked not to be named so that she could speak freely about her institution, tells the story of a chemistry instructor who told his students to 'work together', and then spent the rest of the class time reading. "Active learning done badly is worse than a good lecture," says Leips. A 2011 survey of biology teachers at 77 US universities found that, even though most of them claimed to be using at least some active-learning methods, few of them were doing it properly[6].

Proponents of active learning say that change will come only when innovations are made at every level of a university system (see page 282). To help interested biology teachers to do better, the US National Academies has been running a series of five-day workshops every summer since 2004. "We've had about 1,000 people go through by now," says William Wood, a biologist at the University of Colorado Boulder, and co-director of the programme for its first ten years.

One of the big lessons, says Wood, is that teachers should develop their lesson plans in the same way as they design experiments. Instead of following a textbook or syllabus, they should start with a clear goal — the concepts and skills that they want the students to learn. Then they should choose the instructional methods that will achieve that goal, as well as the methods they are going to use to assess the students' progress.

The summer institutes have undoubtedly done a lot to raise people's awareness, says Leupen, but simply attending a workshop is not enough. "If they come back to the same department full of the same people doing the same things — they will go right back to teaching the old way."

Continuing the support back home is crucial, says Lue. "Science is a team sport. If you're a neuroscientist or a soft-matter physicist, you have seminars, colloquia, luncheons — places you can go on campus to meet with like-minded people and trade best practices." His centre at Harvard is trying to create that kind of community for teaching and learning, he says, and many other US universities are doing the same.

As helpful as such efforts are, they do not get at what many regard as the biggest challenges for active learning. One is the lack of coordination across borders. Educational innovations are clearly happening across the globe (see page 276) and interest in active learning is high. Dirks has received an enthusiastic response to workshops she ran on pedagogy and the responsible conduct of science in Jordan, Turkey, Egypt, India and Malaysia. And leaders such as Wieman say that they regularly get invitations to talk in Europe, Asia and Australia.

Even so, the international flow of ideas is only a fraction of what it could be. The education systems differ between nations, and it is not obvious how lessons learned in one place can be applied elsewhere. What is more, researchers who are trying to get innovations into universities tend to publish in their own languages.

And then there is what Wieman and others regard as the most fundamental obstacle: the university incentive system. Too often, they say, publications and funding are the only things measured for promotion and tenure decisions, which in effect penalizes time spent on classroom innovation. "Until we commit to having teaching be a key role in tenure decisions," says Lue, "we're just paying lip service."

Some scientists say that the increased intellectual respectability of good teaching is beginning to make itself felt. Many small universities such as the UMBC are making it a key part of hiring and promotion decisions. "In our department, you don't get teaching points in tenure decisions unless you've been innovating," says Leupen. Even large research-focused universities such as Harvard are beginning to place more emphasis on instruction. "Because there is a movement, and programmes to impart this knowledge," says Dirks, "people are starting to get it." ■

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