THE VIRTUAL LAB

Confronted with the explosive popularity of online learning, researchers are seeking new ways to teach the practical skills of science.

BY M. MITCHELL WALDROP

The academic world is in upheaval over MOOCs: massive open online courses that make university lectures available to tens of thousands of students at a time. For roughly a year, universities around the world have been rushing to partner with the major MOOC companies in a move that many believe could revolutionize higher education (see *Nature* **495,** 160–163; 2013).

But for many people working in education, MOOCs do not yet take the revolution far enough. Online lectures by video are fine for conveying facts, formulas and concepts, but by themselves they cannot help anyone learn how to put those ideas into practice. Nor can they give students experience in planning an experiment and analysing data, participating in a team, operating a pipette or microscope, persevering in the face of setbacks or exercising any of the other practical and social skills essential for success in science[1]. "You only understand something when you know how to do it," says Chris Dede, who studies simulations for education at Harvard University in Cambridge, Massachusetts. "And that's not possible to abstract in a lecture."

Almost by definition, practical skills have to be acquired through experience. They require the hands-on, problem-solving activities that have traditionally been the domain of laboratory courses, field trips, internships and, eventually, project work in the lab of a more senior academic.

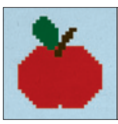
Bringing such experiences online is tricky, but education-technology researchers have been making substantial progress over the past decade. Thanks to smartphones, immersive gaming software and other rapidly evolving technologies, says James Gee, an education-technology researcher at Arizona State University in Tempe, "we can do problem-focused learning way better now" — and can make it available to students around the planet. "It's a way to give everyone the kind of education we used to think of as a luxury," he says.

REMOTE HANDS-ON

In the sciences, the standard vehicle for teaching practical skills is the lab course. "Labs are where we offer students the opportunity to engage with real lab equipment, to analyse authentic data, to experience the wonder of observation," says Mike Sharples, an education-technology researcher at the Open University in Milton Keynes, UK.

But herding students into a conventional lab has never been an option for the Open University, which was founded in 1969 to offer degrees at a distance and now has more than 240,000 students around the world. Until the late 1990s, the science courses would post students kits that might include microscopes, circuit boards, chemistry sets, fish tanks or even lasers. The students would do experiments at home and then post the kits back. But that was expensive and cumbersome, says Sharples.

Today, almost all the lab work is available online through the university's OpenScience Laboratory. Just like many working scientists, students can collect real data from remotely controlled instruments — among them a γ-ray spectrometer for identifying elements and isotopes, and a 0.43-metre telescope in Majorca, Spain. Students can also explore real data with simulated instruments such as the virtual microscope, with which they look at high-resolution images instead of real specimens. "They zoom in, adjust



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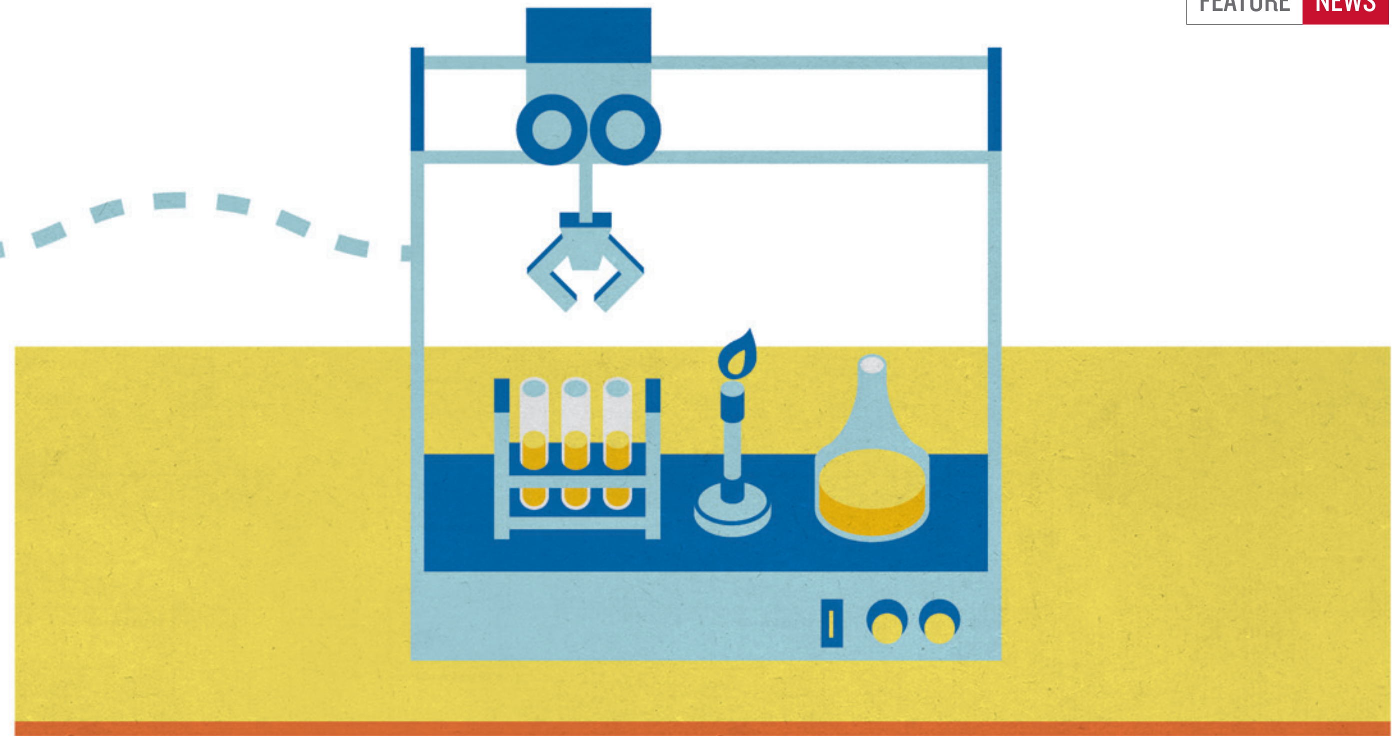

ILLUSTRATIONS BY CHRIS RYAN/*NATURE*

the focus and control where in the sample they're looking," says Sharples — just as they would on real instruments.

Paulo Blikstein, director of the Transformative Learning Technologies Lab at Stanford University in California, is going further, with a new generation of digital lab courses. One example uses remotely controlled instruments at a centralized biology lab — a project he is developing with Ingmar Riedel-Kruse, a bioengineer at Stanford. "The idea is to have a room with 10,000 Petri dishes, each a few millimetres wide, and a robot that works like an ink-jet printer," says Blikstein. "A student would tell the robot, 'Go to my dish and add X drops,' and a camera would watch what happens."

But some researchers worry that a completely virtual lab can never fully replace time at the bench. If students go on to pursue a master's degree or PhD, they could be at a disadvantage in a real lab. "I'm a conservative in this sense," says Beverly Park Woolf, a computer scientist who works in digital education at the University of Massachusetts Amherst. "You should touch the equipment" and get a real sense of what it means to tweak a dial or measure out a reagent, she says.

THE LAB IN YOUR POCKET

Even conventional labs can be disconnected from reality, says Michael Schatz, a physicist at the Georgia Institute of Technology in Atlanta. "Students get the idea that it's all about some specialized room with specialized equipment," he says, "and then they walk back out into the real world, where none of what they learned there applies."

That is why Schatz created Introductory Physics I with Laboratory, a MOOC that started in May and is devoted to the elementary science of motion. One of the first MOOCs to thoroughly integrate hands-on learning, it relies on the fact that these days, virtually every student is walking around with a camera-equipped smartphone. "We start by asking them to go out and capture a video of an object in their environment moving in a constant direction at a constant speed," says Schatz. (Later labs involve more complex motions, such as a basketball arching toward a hoop.) Next, the students analyse their videos using open-source software that extracts the object's position over time. Then they formulate a theory to explain their data and build models to implement it. Finally, they explain their results and their model in a 5-minute video lab report, which is uploaded to YouTube for the other students to discuss and critique online.

It will not be clear how this works with thousands of students until the course is completed in August, says Schatz. But if the approach does prove effective at helping students master the material, he and his colleagues hope that it could be a model for all online science courses.

The Open University is also exploring the educational uses of mobile devices. In 2008 it launched iSpot, in which people roaming outdoors can upload digital photographs of plants, birds, insects, fungi and other organisms, along with their best guess as to what they are. The programme, which is used in some of the university's biology courses but is also open to non-students, currently has some 30,000 participants in the United Kingdom and South Africa.

Each uploaded photograph sparks a lively online discussion about what the organism is and what its presence means to the health of an ecosystem — including comments from scientists who are using the iSpot data for their own studies. "So it's a way of doing practical science outdoors," says Sharples, "but in a collaborative way." In effect, he says, the participants are becoming apprentice biologists.

LAB AS VIDEO GAME

Systems such as iSpot and Schatz's MOOC are heavily influenced by the philosophy of 'enquiry-based' learning. Instead of trying to fill students' heads with knowledge through a lecture or a recipe-style laboratory exercise — telling them the answer, so to speak — enquiry-based learning puts them to work in teams, challenges them with a question and lets them struggle to find their own answer.

A huge body of evidence[2] suggests that such approaches are much more effective than lecture-and-drill-based techniques, says Blikstein. Unfortunately, he adds, "in any big, national-scale debate, these approaches always lose out", in part because they are considered too expensive and time-consuming to use in a classroom.

These days, however, they are finding a natural venue in the multi-user virtual environments (MUVEs) pioneered by online games such as *World of Warcraft*.

A prime example is EcoMUVE, a course on ecosystems developed by Dede and his colleagues at Harvard. Students form teams to spend two weeks exploring a virtual pond and its surroundings. One virtual day, they discover that the fish are dying, and they have to find out why. The teams decide what data to gather: they might, for example, measure run-off of potentially contaminated water from the nearby housing

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development and golf course, monitor changes in pond colour or look at pond life through their virtual microscope.

Next, the teams have to work out how to analyse those data and agree on an explanation for what is happening, applying mathematical concepts and debating causality to understand how distant actions, such as the spread of fertilizer on a golf course, can affect ecosystems. The EcoMUVE software has been tested with school students aged 11–13, who showed substantial gains in their understanding of concepts such as quantitative measurement, food webs and watersheds.

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David Shaffer, an educational psychologist at the University of Wisconsin-Madison, and his colleagues are using a similar enquiry-based approach to develop a virtual internship for undergraduate engineering students. "When kids show up for their first year they're all excited to design and build stuff," says Shaffer. But first they have to spend two years taking maths and physics, and many get discouraged. Instead, Shaffer and his team get them building things right away.

In the exercise, the students are interns at a fictional dialysis-machine manufacturer, and they form teams to design a next-generation system to filter waste from blood. The students do research and run simulations looking at cost, performance and marketability of various systems and then they work together to decide what final experiments to conduct before making their report.

This virtual internship has been tested with students at Wisconsin, the University of Pennsylvania in Philadelphia, and the University of Pittsburgh in Pennsylvania. Before-and-after assessments show that it tends to sustain students' confidence and enthusiasm. Now Shaffer and his collaborators are developing a full simulation-based introductory engineering course, and turning their system into a software platform that can support internships in any subject.

Some educators complain that enquiry-based learning lacks focus and instruction. "If you just let kids interact by themselves in a game environment, they may have fun — but they won't learn much about science," says Art Graesser, a psychologist at the University of Memphis in Tennessee. To address that, designers generally include some kind of digital or human mentor to keep students on task.

One key element in effective mentoring is conversation, says Graesser. "When people just read a textbook or listen to a lecture they get shallow knowledge," he says. But when they talk about the material they start to understand it deeply. Graesser and his collaborators, for example, have developed a system based on 'trialogues', in which a student interacts with two animated computer agents — a tutor and a student — that converse in natural language and adapt their behaviour to the real student's response. Real students can interact with the tutor directly, with the student agent chiming in as a kind of sidekick, or they can deepen their own knowledge by teaching the material to the virtual classmate.

One system that uses trialogues is *Operation ARIES!*, a game designed to teach critical thinking and scientific reasoning to secondary-school and university students. Players sign up with the 'Federal Bureau of Science' to save Earth from aliens who are using bad science to turn humans into mindless consumers. Students work together to evaluate realistic media reports, blogs and press releases. They identify those that have research flaws such as claims that a correlation implies causation, and are therefore evidence of alien activity.

BRINGING IT TOGETHER

One of the biggest barriers to widespread adoption of systems to teach practical skills is that so many are one-off experiments not connected to MOOCs or anything else. Once the project is finished, "you end up putting your app up on an obscure website where almost nobody can find it", says Daphne Koller, co-founder of the largest MOOC company, Coursera in Mountain View, California.

Coursera is trying to change that, says Koller — not only by encouraging experiments such as Schatz's physics MOOC, but also by rewriting its own software so that it can deliver practical apps alongside lecture courses. Once the new version begins to roll out, she says, MOOC instructors should be able to plug in a module for iSpot, for example, or a virtual environment such as EcoMUVE, or a practical-skills app of their own devising. The hope is that this will create a common marketplace for these applications, and give them much wider exposure.

But that is just one example of the tectonic shifts that the MOOC revolution has set in motion, says Shaffer, echoing a point made by many other observers. "Our education system is like a big, old, comfortable, fuzzy sweater," he says. It has lasted forever and seems indestructible. But pull on a loose bit of yarn, say by putting lectures online, and the whole thing starts to unravel. "The way in which the pattern held together before doesn't work anymore," he says.

The fabric is being reknitted even as we speak, he says, with results that no one can foretell. But that makes this moment exciting, he says. "We're in a place that we can begin to think about education in a whole new way." ■

M. Mitchell Waldrop *is a features editor for* Nature *based in Washington DC.*

1. Pellegrino, J. W. & Hilton, M. L. (eds) *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century* (National Academies Press, 2012).
2. Olson, S. & Loucks-Horsley, S. (eds) *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning* (National Academies Press, 2000).

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