When the Pontifical Catholic University of Chile sent students home during the COVID-19 pandemic, Fernán Federici needed to find a new way to teach his biochemistry lab course. Using open-source equipment, which anyone can reproduce and use, he created a lab box filled with tools to allow students to do experiments at home. Distributing the lab supplies didn’t all go smoothly. Mailing the box along the length of Chile caused some delays, and students had to be guided remotely through video calls to make sure everyone was able to use the equipment and understand the experiments. But Federici was surprised at how well the remote course worked.

This past year has been challenging for instructors of undergraduate chemistry courses. It’s hard enough to convert in-person lectures to engaging online content, but remotely teaching a lab course requires a whole new level of creativity. Some departments postponed courses; others relied on online videos or emphasized data analysis.

Teaching groups of students as they stand side by side at lab benches has been the gold standard of chemistry education since the 19th century. It’s how generations of chemists have learned how to follow a protocol and how to do basic lab techniques. But those standard experiments aren’t always representative of current research techniques and don’t reflect how researchers work. Some instructors and universities saw the lockdown as an opportunity to completely rethink the way they teach their science students.

Finding the right tools
One of the challenges for instructors who want to move away from lab courses is finding tools that still teach their students the skills that they would have learned from hands-on experimentation.

Eamonn F. Healy was in the middle of teaching his organic chemistry course at St. Edward’s University when the COVID-19 outbreak forced students off campus in March 2020. Healy had planned to teach a retrosynthesis module with a lab component after spring break, but like many other chemistry instructors, he was forced to quickly find a way to teach the same concepts online. “I put videos and animations up on the web, but they were going to have to step through mechanisms without my daily guidance in the classroom,” he says.
Like Federici, Healy found a creative solution. He had been following the latest online chemistry tools and had found IBM’s artificial intelligence-driven tool RXN for Chemistry, which helps chemists predict reactions and design retrosynthesis pathways. Healy quickly created a new set of activities for his students, tailored to learning at home. The adapted course content asked students to design a retrosynthesis using RXN rather than follow or memorize a given reaction.

At IBM Research in Zurich, Teodoro Laino noticed an increase in the total number of reaction mechanisms requested on the RXN platform after many scientists around the world left their labs in April 2020. While much of the activity was the result of chemists planning reactions from home, Laino wasn’t surprised to learn that part of the increase in use was due to students using the tool in their courses. “People will always find dozens of ways to apply the technology.”

Adapting the course using RXN worked for Healy. He noticed that his students—despite not having the in-person support they would have had in the lab—were getting a more realistic experience because they had to plan their own reactions rather than follow step-by-step guidance. “The fact that it is a true functioning expert system was a huge advantage,” he says.

Finding new ways to use existing technologies was the fastest way for educators like Healy, Federici, and many others to quickly adapt lab classes to distance learning. The different open-source kits that Federici combined to create his lab box were not necessarily created to be part of an undergraduate class. These kits included a small polymerase chain reaction machine to amplify DNA, a fluorescence detector, and reagents to carry out experiments.

One of the people Federici collaborated with to create the lab box was Guy Aidelberg, a Ph.D. student working with Ariel Lindner at CRI, an interdisciplinary research center at the University of Paris. A few years ago, Aidelberg and Lindner developed an easy-to-use genetic testing kit to help fight the Zika outbreak in Brazil. The kit included reagents and materials that allowed anyone to detect the Zika virus, even without access to a lab. This inspired them to think about ways to get more people to learn basic genetics experiments. After the Zika kit, Lindner says, “we took a step back and thought: What kind of DNA detection can everyone do in their own kitchen?”

This led Aidelberg to develop GMO Detective, an open-source set of protocols and instructions for finding reagents and basic equipment for running an experiment on food to see if it contains certain DNA sequences indicating genetic modification. It’s one of the kits that Federici included in the lab box for his students. The materials were created for citizen scientists and high school students, so Federici’s biochemistry undergraduates found them easy to use. Aidelberg thinks that the best way to learn is to have students explore on their own—and make mistakes along the way. “You learn way more when it all works exactly like it’s supposed to,” he says.

Rethinking teaching
Federici and Healy each took a very different approach to adapting their courses to distance learning, but both of them noticed that their students were obtaining skills that would have been hard to teach in traditional lab classes, where students often follow the same protocols at the same time to come to a predefined goal. In the updated courses, students were working more independently, which gave them the confidence and ability to learn from their mistakes or to follow a protocol on their own.

What started as emergency solutions in response to the pandemic got the professors thinking about the way they taught. “What I want to do with my students as much as I can is show them what real chemistry is like,” says Healy, who plans to keep using tools to let students explore chemical reactions on their own. Federici, meanwhile, wants to incorporate open-source kits in his future lab courses, even when classes are back on campus, to allow students to work together in small groups rather than all crowd around the same machines.

Chemistry instructors who want guidance on how to adapt their courses to distance learning can look to institutions that have designed their entire science curricula with minimal in-person contact hours. Abha Ahuja, formerly a lecturer and curriculum fellow at Harvard Medical School, is an associate professor of natural sciences at Minerva Schools at KGI, a university where students learn online while spending each semester in a different city around the world. When Minerva was launched less than a decade ago, Ahuja and other faculty were able to reflect on the skills they wanted their science graduates to have. “And when we looked at that list, we realized that you don’t need a high-tech laboratory and a white coat,” Ahuja says. In designing the curriculum, “we had the privilege of starting from scratch.”

As part of a revamped organic chemistry course, students at St. Edward’s University used IBM’s RXN for Chemistry platform to design a retrosynthesis for the antimalarial drug hydroxychloroquine. Credit: J. Chem. Educ./Courtesy of International Business Machines Corporation, © International Business Machines Corporation.
Minerva doesn’t have labs. It doesn’t even have its own campus. Instead, students learn through a proprietary online teaching platform and acquire practical experience through internships. For students interested in a lab-based career, their entire practical training comes from internships in research labs.

Xiaotian Liao, who was part of Minerva’s first graduating class in 2019, works as a research assistant in Vijay Sankaran’s lab at Boston Children’s Hospital and Broad Institute of MIT and Harvard, where she researches the genetics of blood-cell-production disorders. She did an internship in the same lab as a student, despite not having taken any undergraduate lab courses. “I didn’t even know how to pipette,” Liao says.

For a group to take on a student without basic lab experience might seem like a risk, but Ahuja has been pleasantly surprised at how research groups like Sankaran’s have responded to Minerva students. “Any lab that has accepted a student from us in the past has welcomed another one.”

Another remote university, the Open University (OU) in the UK, has decades of experience in distance learning. “When the university started in the 1970s, they used to send out home experiment kits,” says Eleanor Crabb, director of teaching for OU’s School of Life, Health, and Chemical Sciences. Since then, the school has found other ways to engage students from a distance. For example, students can book time on an automated titrator set up in an OU lab in Milton Keynes, England, and control it from anywhere in the world. Or they can watch a live “labcast” and interact with one of the university’s staff members as the person does experiments in the lab.

Crucially, some in-person contact is still required for OU’s chemistry students. “We cannot entirely replace the hands-on experience of the lab,” says Maria Velasco-García, a senior lecturer in analytical sciences who leads curriculum design for chemistry at OU. To learn practical skills that can be acquired only in person, such as carrying out an organic synthesis, students meet for a short summer course. But by using remote teaching to cover the preparation and analysis aspects of the course, the school has minimized contact hours.

Challenges ahead
Although Minerva and OU have found ways to teach chemistry lab skills remotely, they had to carefully consider all the challenges that came with remote teaching and find ways to adapt. But their experience could provide helpful advice for any chemistry departments considering a departure from traditional lab courses.

One challenge for remote chemistry education is providing a safe environment, particularly if students are doing experiments at home. OU no longer mails kits because of safety concerns, and when Federici designed his traveling lab experiments, he had to make sure to use reagents that could be sent by post and used safely at home. Some of Minerva’s students who do experiments at home use regular kitchen equipment as part of a biochemistry module on food fermentation.

An automated titrator (top right) at the Open University lets students control experiments remotely via a computer interface. Credit: The Open University.

If students later work in a research lab, they will need to learn safety procedures, but many research institutes regularly train all incoming staff. For example, Liao says that her lab has a manual ready for any new group members. Basic skills like pipetting, pouring liquids, or reading specialized equipment can also be learned very quickly in a research lab—as long as labs are willing to train incoming interns.

Without a centralized teaching lab, however, evaluating student performance can be more complex. “One thing I did have to adapt for the course is the grading,” Healy says. “I’m never looking for a correct answer. I’m looking for reasonable analysis.” Similarly, Ahuja evaluates students’ general understanding and communication of their work, even if they all worked on individual projects. “We might assess them on their data visualization, for example, or how they applied statistical tests.”

Finally, one downside of fewer lab-based contact hours for science courses uniquely affects chemistry degrees. For a degree to be approved by the American Chemical Society, students need to be in an in-person lab for a certain number of hours. (ACS publishes C&EN.) The same is true for chemistry degrees accredited by the Royal Society of Chemistry (RSC) in the UK.

Unsurprisingly, many universities did not reach the minimum number of contact hours this past year, which
has prompted the ACS Committee on Professional Training to propose adjusting the guidelines for the period when regular lab courses were disrupted and the RSC to allow some practical hours to be replaced with virtual labs. But if course instructors continue to teach with fewer contact hours in the lab, accrediting bodies may need to consider permanently changing requirements for chemistry degrees.

Still, lab courses are unlikely to completely disappear, as students who are planning a future career in research will need some lab training eventually, whether that’s in a traditional lab course or, as Ahuja suggests, in an internship in a research lab. She explains that a research lab might be a better option, because “we want our students who want to learn a particular technique to do it in the authentic setting.”

Even IBM’s Laino, whose work touches on what the chemistry lab of the future might look like, sees the benefit of lab-based training. He is working on RoboRXN, which links RXN with automated, remotely controlled lab equipment. “However, there will always be the case where something will not work,” he says, so eventually, someone is going to have to step into the lab and handle the equipment.

That’s why Laino thinks that, despite all the technological advancements, we shouldn’t forget traditional lab training entirely: “Not because that’s the way we want to continue to do chemistry but because we want to build a better way of doing chemistry in the future.”

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