The sudden switch from predominantly in-person to remote learning across all levels of education due to the COVID-19 pandemic posed many challenges, including transitioning in-person active learning efforts to an online format. Although active learning has increased student engagement in science, it can be challenging to effectively integrate into remote courses. Adapting in-person classroom approaches to maintain timely and effective communication, provide equitable access to course materials, and encourage class participation in remote environments proved especially difficult for many instructors engaging in remote learning during the pandemic, often for the first time. As instructors of in-person undergraduate introductory biology courses, we present three different solutions developed during the pandemic to address the challenges of adapting an experiential hands-on activity, an interactive lab, and a research project for remote learning. We found that instructors can leverage the flexibility of the online environment and use existing remote tools to expand active learning possibilities and create meaningful classroom connections, even at a distance.

PERSPECTIVE

Active learning techniques, such as small group exercises and discussions (1), enhance student learning experiences and performance in science courses (1–4). However, the abrupt transition from in-person to fully remote instruction in response to COVID-19 during spring 2020 presented three major challenges for engaging introductory biology students in distance-based active learning. First, maintaining timely and effective communication between instructors and students became more difficult (5), especially when students had unreliable Internet connections (6–8) or were joining from disparate time zones. Second, providing students with necessary course materials, including supplies for lab exercises and documents for research and discussion, became more challenging, as these resources had to be accessible for multiple instructional modalities (9), especially to students located in different places. Third, the hands-on experiences that are a hallmark of observations and lab exercises in science courses could not readily be replicated remotely (10, 11). Furthermore, students often struggle to maintain focus in an online environment (12), even if the instructor is the same one who taught the in-person course (13, 14). These challenges are not new to distance learning (15, 16), but were magnified during COVID-19 due to the significant rise in numbers of remotely enrolled undergraduates. The pandemic created a unique set of circumstances, in which many students and instructors inexperienced with distance learning found themselves pivoting unexpectedly to remote delivery.

As instructors of undergraduate seminar-style biology courses composed of about 25 students located around the world, we found that converting in-person class activities for remote learning during COVID-19 necessitated course innovations and expanded learning opportunities beyond what had been possible in a physical classroom. Here, we document how three such distinct approaches in our introductory biology seminars on life science and environmental science emerged as ways to address the challenges posed by remote learning. These activities cover three key topics: diversification and evolution, Mendelian genetics, and environmental health, each with learning objectives based on aspects of active scientific inquiry derived from the Next Generation Science Standards, which transfer usefully and uniformly to the introductory college level (17). The switch to a remote environment provided opportunities to reassess which learning objectives could only be communicated and achieved through synchronous, real-time instruction (18) and which could be better met through asynchronous, self-paced coursework (9). Additionally, the transition to delivering content online necessitated further development of equitable access to course materials (19–21). In some cases, this offered chances to capitalize on experiential learning sources outside of the classroom that were enhanced by students being in different places. Lastly, encouraging active
participation and collaboration in remote settings was achieved through a variety of widely available, accessible, and secure technology platforms, including learning management systems and the G Suite for Education (https://edu.google.com/), which gave students a range of different options to engage with course material (22–24).

Productively adapting in-person active learning approaches to remote learning during the COVID-19 pandemic required consideration of how and when students were interacting with course materials, how accessible these materials were for all students regardless of time or place, and what modes of engagement encouraged active participation. We first document how an outdoor, in-person, hands-on exercise was modified into an asynchronous experiential learning activity. Next, we outline methods used to transition an in-person group laboratory exercise into one conducted remotely in a synchronous class. Lastly, we explain how collaborative research projects can be adapted for remote learning using a combination of synchronous and asynchronous methods. In each section we discuss how these solutions contributed to reimagined and enhanced approaches to active learning in introductory biology while still retaining, and indeed, expanding upon the learning objectives from in-person experiences.

**Activity 1: Achieving Remote Experiential Learning**

The scientific process often starts with tactile observations (25), and learning how to make observations and connect them to scientific inquiry is a crucial objective in our introductory biology seminar. During the unit on diversification and evolution, students venture outside to make structured observations about the plant diversity in a nearby park. To recreate this hands-on activity in a remote environment, students needed to engage in similar experiences from different locations. Additionally, for equity purposes and particularly during the COVID-19 lockdowns, students had to be able to accomplish the tasks without purchasing additional supplies, or traveling away from their current locations. To address these issues, a collaborative asynchronous activity, in which students conducted observations outside of class, with widely available and readily usable tools, emerged as a solution. Entitled Backyard Biodiversity, the remote activity capitalized on the diverse range of natural environments students relocated to during the pandemic, retaining the same learning objectives as the in-person version: 1) Observing local adaptations of plant traits, 2) Comparing plant diversity in different locations, and 3) Identifying examples of convergent and divergent evolution.

In the first part of the exercise, students were given 48 h to take a 30-minute walk around their neighborhoods and identify 20 unique plant species. The activity was designed to be conducted locally at any time that worked safely for the student. Plant identification was mostly accomplished through Seek (https://www.inaturalist.org/pages/seek_app), a free application that uses smartphone cameras to identify plants and other organisms in real-time through machine learning. If a student did not have access to a data plan, they could take pictures of the plants and then, once back on Wi-Fi, upload the images to Seek for identification. Students without smartphones and those who could not go outside were asked to complete the task using online field guides for local parks. Plant identification could thus be accomplished with no additional purchases and without an instructor present. The results speak for themselves; in the spring of 2020, 60 students with no background in botany independently identified over 1,200 species of plants around the globe.

After data collection, each student was paired with someone living elsewhere. The pair had 2 weeks to create a presentation comparing their species’ lists. They specifically addressed these questions: (i) How many species occur in both environments? (ii) Which species pairs represent divergent or convergent evolution? (iii) What plant traits are observed in a single environment or in both environments? and (iv) How is plant diversity in both locations similar or different? Each group presented their results and analysis in 3-min pre-recorded presentations in Zoom (zoom.us) posted on the course’s learning management system. In place of a synchronous class period, the students were given 48 h to peer-review the other presentations using a Google Form (http://forms.google.com/).

Conducting all aspects of the activity asynchronously allowed students to leave their computers and actively engage with the natural world and their peers flexibly, according to their own schedules. Benchmarks along the way, including submission of a Google Form for the plant identification as well as a presentation draft for instructor review, kept students on track during the asynchronous activity. The distance-based learning infrastructure provided unique opportunities for plant observations and comparisons to occur around the world, in contrast to the in-person version that only assessed different areas of the same park. Despite being confined to one place during COVID-19, students experienced nature from both local and global perspectives, directly from their personal experiences as well as those of their peers.

**Activity 2: Designing a Remote Interactive Virtual Lab**

As in many high school and college biology courses, Mendelian genetics is a key topic in our introductory biology seminars, because it is both foundational to understanding many other ideas and is a common source of students’ scientific misconceptions (26). Studies have shown that students learn more about this topic when illustrative examples from humans, rather than from other species, are used (27), and that team-based approaches to learning genetics are both enjoyable for students and particularly effective at
promoting performance on knowledge assessments (28). Based on this research, as well as on our own experiences in the classroom, our approach to teaching Mendelian genetics in person involved an active-learning classroom exercise during which teams of about four students recorded each other’s phenotypes for traits identified as exhibiting Mendelian patterns of inheritance [e.g., hand clasping, earlobe shape, iris pigment, freckles, “Hitchhiker’s thumb,” mid-digital hair, phenylthiocarbamide (PTC) tasting, tongue rolling, and Widow’s peak]. Class data collected through these observations were then analyzed and used to discuss related scientific concepts and misconceptions including alleles, genotypes, dominant and recessive traits, Mendel’s Laws of Segregation and Independent Assortment, Punnett squares, continuous and discontinuous variation, sample bias, human error, and non-Mendelian inheritance. Students were consistently more engaged and interested in this activity than almost any other class exercise, and performance on assessment questions related to these concepts was higher than the average on other questions in the same exam.

When the COVID-19 pandemic prompted a shift to remote instruction, this activity became impossible to complete without substantial modification. One alternative approach was to use virtual labs; at least one published article pre-dating COVID-19 reported that a Mendelian genetics virtual lab effectively promoted learning of Next Generation Science Standards CrossCutting Concepts and Life Sciences Core Ideas (26). While the activity described did not focus on human traits, there are at least two virtual exercises dedicated to human Mendelian genetics available through Cold Spring Harbor Laboratory (http://www.dnaftb.org/14/problem.html) and Labster (https://www.labster.com/simulations/mendelian-inheritance/). Virtual labs have been successfully used as lower-cost alternatives to their in-person counterparts, and as engaging learning opportunities in online classes. They are thus likely to become increasingly popular as the pandemic prompts potentially long-lasting shifts toward online learning and expanded use of educational technology. While virtual labs can effectively promote learning in biology courses, they do have some drawbacks, including loss of or reduced interaction and collaboration among students unless properly designed and implemented to preserve these aspects (29). Because virtual labs often include a number of steps completed individually and asynchronously, their use presents challenges for providing timely and effective formative feedback to students, especially for those working in a different time zone. Additionally, virtual labs made available by outside vendors were not as intensively supported by our university as other technologies such as Zoom (which was fully integrated into our learning management system), so students with unreliable or low bandwidth Internet connections might encounter additional barriers to fully accessing virtual labs.

Concerned that these drawbacks would reduce class participation and engagement, we conducted this activity during synchronous Zoom sessions in which small groups of students collaborated in Zoom breakout rooms and recorded their phenotypes in a Google Doc that was later shared with the class. The middle portion of the class period was then used to complete a worksheet with questions about their observations and underlying biological concepts, which was followed by a return to a full-class discussion of key findings and questions. This activity successfully engaged students and promoted learning gains by preserving a focus on human traits, and the ability to observe classmates’ faces, while facilitating valuable student interactions during the collection, analysis, and discussion of class-generated data. Participants were given the option to participate with their cameras off, but in this class all 20 students attending class synchronously kept their cameras on. The small number of students unable to attend synchronously later accessed the materials individually. Even so, having most students complete the activity synchronously facilitated timely and effective communication between students and faculty and encouraged class participation that could also be readily evaluated. While access to Zoom and Google Docs was integral to the way we conducted this activity, faculty who do not use these tools might employ alternatives available in their learning management systems, such as forum tools to post and discuss photos and data, and chat functions to promote synchronous discussion. Such alternative approaches may also be useful for classes with large numbers of students who do not attend synchronously.

**ACTIVITY 3: ACTIVELY ENGAGING STUDENTS IN REMOTE RESEARCH**

Research is a cornerstone of our biology seminars, but many of our introductory students have scant prior scientific research experience, even in the form of a literature review. Direct and immediate guidance for accessing resources, engaging with the material, framing arguments, and reporting findings is often required, and the challenges posed by these tasks can be exacerbated when participants work alone (30) on complex scientific matters of potentially little interest (31–33). Before the pandemic, to address these issues and actively engage our introductory environmental science students in scientific research, we applied active learning tools including think-pair-share, small group discussion, peer review, round-robin, and jigsaw ([34], N. Salim, 2020, The Aga Khan University [https://docs.google.com/document/d/16PpcXB5Z9e8WiFwYclMfFLv2BQidY-GzC22VXtzonk/edit]) to literature-based group research projects. In person, over the course of one or two time intervals, students formed groups to begin researching, and later present, on biodiversity conservation case studies of their choice, such as Amazon deforestation, the illegal wildlife trade, and the White-Nose Syndrome (WNS) disease decimating bats.

The emergence of the SARS-CoV-2 pathogen provided teachable moments and opportunities to upgrade this activity to a comprehensive and engaging online exploration of
environmental health through the lens of the pandemic that students were experiencing in real time. Initially, most class members had an anthropocentric, or human-centered, perspective focused on COVID-19 effects and prevention in people. Further, many were confused by the rampant misinformation and disinformation, including a conspiracy theory that the virus was created in a lab for nefarious purposes, and that bats were to blame and should therefore be exterminated (H. Kaur, 13 March 2020, CNN [https://www.cnn.com/2020/03/04/health/debunking-coronavirus-myths-trnd/index.html]). However, by exploring how humanity’s expansion into wild environments containing myriad pathogens, together with the export of organisms through consumption and the wildlife trade, led to the pandemic, students were able to counter misconceptions and expand their limited perceptions of environmental health from a tendency to focus on humans, to a broader and more biocentric approach encompassing human effects on wildlife as well.

To adapt the more traditional group research projects used before COVID-19 to the remote environment, we made several adjustments and balanced synchronous and asynchronous modalities. First, in a synchronous Zoom session, previously assigned semester-long “class buddies” conducted a think-pair-share review on their definition of environmental health, using the university learning management system’s chat or a free online platform such as Google Chat. Background information supplementing the assigned readings was then provided by the instructor, and the research project guidelines were covered. To accommodate students in different time zones or with Internet connectivity issues, the session was recorded, the chat was left open, and flexible remote office hours were offered. A list of potential case studies at the intersection of COVID-19 and ecosystem health was shared with the class via a Google Doc containing links to related, freely available news stories and academic publications, which was regularly updated. The students as well as the faculty had editing permissions so that everyone could curate the resources, access research materials regardless of location and library experience, and sign up to join a group based on shared time zones or interests.

Next, each student group met online outside of class at their convenience to plan and eventually produce a 10- to 15-minute presentation on their chosen case study using a shared platform such as Google Slides and/or a Zoom recording. The presentation had to include scholarly sources as well as news articles, and each group was required to explain their case study, address any misconceptions, cover significance, threats, and strategies, and pose questions for student-guided discussion. In a synchronous recorded Zoom session, students presented to the class and guided a discussion based on those questions. Participants unable to attend synchronously could submit presentation recordings and discuss via a shared Google Doc or another online forum. Similarly, large classes with many groups could meet in subsets or participate asynchronously. Assessment was carried out by the instructor and student peer-reviewers using a rubric shared with students beforehand. Finally, in a class (or section)-wide synchronous round-robin discussion, each student, either in real time or later online, compared and contrasted the different case studies, which could be seen as puzzle pieces that, when put together, revealed a more realistic and biocentric view of environmental health.

Adapting an in-person, on campus, research project to a remote setting thus allowed students to engage with topical and dynamic case studies and rapidly incorporate recent updates. The transition also enhanced student communication and collaboration during and outside of class through asynchronous and synchronous means. The framework can incorporate different topics and case studies and thus is flexible enough to be used for remote research projects in a range of introductory and advanced biology and public health courses, and beyond.

CONCLUSION

The spread of COVID-19 disrupted human civilization, including all levels of education, in unprecedented ways. While distance-based learning is not a new phenomenon, never before has it been attempted on its current global scale, with students who may have no choice but to participate remotely. Advances in technology have made teaching online more feasible and dynamic, and can be used to address the challenges of adapting in-person active learning to remote settings. The process of reimagining in-person learning for remote arenas can be difficult, and few educators had much experience with this before COVID-19 (9, 21, 35). The three collaborative activities discussed here demonstrate that the transition can be approached via fully asynchronous, fully synchronous, and hybrid methods. The activities can also be used in any undergraduate introductory biology course, and potentially adapted to senior high school and other fields as well. Widely available technological tools can enhance student experiences and be used to achieve the same learning objectives as would be achieved in-person. The experience of rapidly adapting these collaborative exercises for a remote environment provided novel opportunities for innovation and creativity beyond the physical campus. Furthermore, students can now engage with course materials via a more diverse set of tools and resources and gain more control over how and where they learn (9, 21). The constraints imposed by COVID-19 have facilitated meaningful connections and collaborations among students and instructors, perhaps representing a silver lining to the crisis, with potential ongoing benefits for future in-person and remote instruction.

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