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Triage and Recovery of STEM Laboratory Skills

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The global COVID-19 pandemic left universities with few options but to turn to remote learning. With much effort, STEM courses made this change in modality; however, many laboratory skills, such as measurement and handling equipment, are more difficult to teach in an online learning environment. A cohort of instructors who are part of the NSF RCN-UBE funded Sustainable, Transformative Engagement across a Multi-Institution/Multidisciplinary STEM (STEM^2) Network (a working group of faculty from two community colleges and three 4-year universities) analyzed introductory biology and chemistry courses to identify essential laboratory skills that students will need in advanced courses. Seven essential laboratory proficiencies were derived from reviewing disciplinary guiding documents such as AAAS's *Vision and Change in Undergraduate Biology Education,* the American Society for Microbiology's *Recommended Curriculum Guidelines for Undergraduate Microbiology Education*, and the American Chemical Society's *Guidelines for Chemistry*: data analysis, scientific writing, proper handling and disposal of laboratory materials, discipline-specific techniques, measurement, lab safety and personal protective equipment, and interpersonal and collaborative skills. Our analysis has determined that some of these skills are difficult to develop in a remote online setting but could be recovered with appropriate interventions. Skill recovery procedures suggested are a skills "boot camp," department and college coordinated club events, and a triage course. The authors recommend that one of these three recovery mechanisms be offered to bridge this skill gap and better prepare STEM students for upper-level science courses and the real world.

INTRODUCTION

In response to the COVID-19 pandemic, universities across America (and the world) sent students home and attempted to pivot seamlessly to remote learning in an effort to continue to educate under chaotic circumstances. While most aspects of STEM courses are amenable to this change in modality, the teaching of many laboratory skills does not translate to an online learning environment. To compound the complication of lost lab skills, Kolack et al. reported as much as 5% of students were unable to finish the spring 2020 semester due to personal, access, or technology reasons (1). The number of these students who are permanently unable to continue their education will remain unclear until in-person classes are reestablished.

The fall of 2020 revealed that many students were still not able to attend face-to-face laboratory courses for a variety of reasons including personal illness, fear of infecting self or family members, and travel restrictions. In fact, out of an abundance of caution, some schools still opted to postpone in-person classes. However, when student feedback and registration data is taken into account, recent studies indicate students prefer face-to-face delivery of laboratory material (2–4). In spite of this, most universities have no choice but to develop online versions of labs for those unable to attend in person.

In the present report, using the American Association for the Advancement of Science *Vision and Change in Undergraduate Biology Education*, the American Society for Microbiology's *Recommended Curriculum Guidelines for Undergraduate Microbiology Education*, and the American Chemical Society's *Guidelines for Chemistry*, we identify critical skills that are potentially underdeveloped or lost when teaching online relative to when teaching students in a face-to-face laboratory setting (5–7). Although virtual labs have been conducted for years outside of a pandemic setting,

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most educators argue that virtual labs are better used to supplement face-to-face instruction, not replace it, as noted by the ACS (https://www.acs.org/content/acs/en/policy/publicpolicies/education/computersimulations.html) and others (8). We propose three mechanisms that universities can use to triage and recover these important skills and keep students from falling behind in their academic pursuits. In order to develop a meaningful and applicable approach, we restricted our focus to the laboratory portions of first-year courses in the STEM fields of chemistry and biology as these serve as the foundation of many upper-level science courses. These courses are introductory level, standard requirements for many majors and non-majors in 2-year community colleges and 4-year institutions alike. In contrast, the lower enrollment in upper-level courses makes it easier for individual departments to meet these students' needs, while the numbers of introductory level students are greater and make the situation far more difficult to handle at the individual class level, and also require the backing of administration. However, we hope this report may serve as a model to those considering what course of action is needed to triage and recover lost skills at any level.

METHODS

A cohort of instructors who are part of the NSF RCN-UBE-supported Sustainable, Transformative Engagement across a Multi-Institution/Multidisciplinary STEM (STEM^2) Network, a regional network of faculty from two community colleges and three 4-year universities organized to collaborate and transform undergraduate STEM education (9), analyzed the introductory STEM courses (Biology and Chemistry I and II) to identify core laboratory skills that students will need in more advanced courses. The skills in each course were categorized into three subgroups: (i) skills that could be developed in a remote learning environment; (ii) skills that would not be developed in a remote environment unless there are supplementary materials; and (iii) lost skills that could be recovered using a method we discuss below. After categorizing dozens of skills in the core laboratory courses, it quickly became clear that there is significant overlap in the skills between chemistry and biology in first and second semesters. We then identified what we termed "proficiencies" or umbrella categories under which the skills were grouped (Table 1). For example, the proficiency "measurement" encompasses a range of skills from basic mass, length, volume, and temperature determination (with appropriate significant figures) to pH measurement, concentration determination, and spectrophotometric measurements. This category also includes being able to identify the best equipment to make those measurements (e.g., a beaker compared with a graduated cylinder). The proficiencies and the detailed skills they comprise (placed in the most fitting category, though not mutually exclusive) are listed in Table 1.

In analyzing these proficiencies, the large variance in the online student experience must be taken into account. Some students taking asynchronous labs may never directly engage with their instructor or classmates. Students in a synchronous lab may engage with their instructor and peers regularly and be required to have cameras on with focused discussions and well refined online labs (10). Recognizing that some laboratory classes have turned to hybrid modalities (e.g., meeting in-person every other week or other variations); still others are completely back to in-person meetings. Our analysis is restricted exclusively to virtual laboratories. Here we also note that some institutions have placed restrictions on their instructors. While professors at some universities are permitted to require students to turn on their cameras and interact with the class, other universities have informed their professors that they cannot require either cameras or microphones to be turned on for labs or class. Not using video or audio during the class limits the interpersonal and collaborative work between the students. With these variations of student experiences in mind, the proficiencies were analyzed.

RESULTS

Overall, seven key proficiencies were identified that are normally developed in first-year chemistry and biology laboratory courses (Table 1). Out of these seven proficiencies, only the first two, Data Analysis and Scientific Writing, are likely to be developed in an online laboratory setting. The following four proficiencies in Table 1, including Proper Handling and Disposal of Laboratory Materials, Discipline-Specific Techniques, Measurement, and General Lab Safety and Personal Protective Equipment (PPE), were recognized as lost skills in remote or online environment, but recoverable. One method some universities have implemented to minimize the skills lost while teaching remotely is the use of standard or self-created take-home kits (11, 12). However, such kits are not a complete solution, as they do not fully cover all skills in any one proficiency. Further, there are some issues with these kits including: safety, distribution, and cost (discussed further below).

One proficiency that can be difficult to develop in the virtual format is Interpersonal and Collaborative Skills. In a typical laboratory setting, students frequently work in groups of two or more to conduct experiments and analyze results together and is an important factor in student learning (13). While students in virtual laboratory classrooms can be assigned into groups via breakout rooms, students are rarely observed turning on their microphones or web cameras but rather typing in the chat box. This is particularly true among the authors whose institutions do not allow them to require camera or microphone usage. It is our experience in a virtual format that students are less inclined to communicate verbally with each other to discuss and solve complex problems than they are in a face-to-face setting. While this is class and instructor dependent, we observe students waiting for one student to answer the

TABLE 1
Proficiencies and essential skills

Proficiencies	Traditional laboratory skills	Covered in Virtual Labs	Potentially covered in Virtual Labs with Home Kit/Household Items	Recoverable with One of Our Interventions
Data Analysis	Generating hypotheses			
	Testing, and refining hypotheses			
	Generating and interpreting graphs			
	Creating and using standard curves			
	Using appropriate significant figures			
Scientific Writing	Maintaining a laboratory notebook			
	Writing weekly laboratory reports			
Handling and Disposing of Laboratory Materials	Dissection instruments			
	Acids and bases			
	Solutions			
	Live microbes, plants, and animals			
	Preserved specimen and their dissections			
	Gel electrophoresis			
	Solid waste			
Discipline-Specific Techniques	Aseptic technique			
	Titrations: standard, redox, back			
	Dissection of preserved specimens			
	Calorimetry			
	prepn of and staining a wet mount			
	prepn of a Gram-stained specimen			
	Use of Buchner funnel			
	Proper use and handling of compound, light microscope, stereomicroscope			
	Visualizing prepared slides			
Measurement	Mass			
	vol			
	Length			
	pH			
	temp			
	concn			
	Pressure			
	Selection of equipment best used for specific measurement			

(Continued on next page)

TABLE 1 (Continued)

Proficiencies	Traditional laboratory skills	Covered in Virtual Labs	Potentially covered in Virtual Labs with Home Kit/Household Items	Recoverable with One of Our Interventions
	Absorbance/transmission via spectrophotometry			
General Lab Safety and Personal Protective Equipment (PPE)	Protective Clothing (Gloves, Goggles, Coats)			
	Working with flames			
	Hot equipment			
	Hazardous chemicals			
	Eye wash and safety shower			
Interpersonal/Collaborative Skills	Working with a lab partner			
	Working with a group of students			
	Collaborative Writing			

The essential skills extracted from the guiding disciplinary documents were organized into categories the authors termed "proficiencies." Many of these skills can fall into multiple categories as they are not mutually exclusive. They were then evaluated on the likelihood that they could be developed in an online or remote environment (light gray), or if they would be lost in that environment, and whether our mechanisms could allow students to recover those lost skills. Some skills can easily be covered in a virtual environment while others require some sort of intervention (dark gray) such as using household items or a take-home kit. Interpersonal/Collaborative skills may be achieved in an online setting as long as the instructor encourages/requires this work (black). All lost skills can be recovered through our on-campus interventions.

question, or their professors to provide an answer. This decreased motivation to speak up and increased ability to hide behind their screens (lurking behavior) significantly diminishes the likelihood that learning collectives (study groups) which have been shown to enhance learning through peer-to-peer collaborations will be effective (14, 15). Furthermore, without meeting each other in a laboratory setting, students miss the opportunity to personally see other students that look like themselves. In particular, minority students who can identify other students that look like them can help them gain a sense of belonging in that course (16).

The virtual environment also changes the interactions between students and professors. Without the face-to-face environment, particularly when there is no audio/web camera on, it is hard for faculty and students in the same classroom to read and recognize each other's body languages and facial cues. Sathik and Jonathan showed the importance of facial expressions and body language when trying to understand if students are struggling to learn the content (17). These missing human elements are very important for students to develop their interpersonal skills and can make future job prospects more difficult if faculty find it harder to connect with students, and are less likely to write letters of recommendation (18).

Skill recovery procedures

With the prospects of multiple highly effective COVID-19 vaccines on the horizon (https://www.cdc.gov/coronavirus/2019-ncov/vaccines/index.html) the timeline for their roll-outs and for a possible return to full in-person classes remain in question. In this light, we determined strategies that colleges and universities could take to help students learn as many proficiencies as possible until full face-to-face classes resume.

Take-home kits

This option is available by faculty creating their own kits or by purchase through vendors. Such kits allow students to do some simple and safe experiments at home. The identified skills that can be learned using these kits are seen in Table 1. Two issues arise from the use of kits. The first issue is that schools could be legally liable for the chemicals or other lab materials sent to students' homes. At home, unsupervised students may perform "unauthorized" experiments whereas in a lab setting, this can be controlled. The second issue is that kits tend to be expensive, which can limit not only what is in the kits, but also the schools that are willing to require students to buy them. For example, it is much less likely that community colleges are willing to put this extra financial burden on their students. An argument could be made that a $100- to $200-kit versus the overall cost of the course is not a significantly bigger burden. A possible impact is that kits could help students engage more with the class and feel more connected to other students and the actual science they are supposed to be learning. For students who require financial aid, the extra costs of the kits may make students choose another course.

In-person during the pandemic

While the pandemic persists, college-age students tend to be in a low-risk group and many are willing to come to the lab in-person even if the lecture is still online. Presently, two potential methods to use labs safely and still learn all proficiencies are:

(1) Have half of the students come to the first half of the lab section and have the other half of the students come during the second half. This is intended to decrease the number of students in the classroom to the point that students could physically distance while wearing masks and other appropriate PPE. In this instance, labs would need to be reworked to be much shorter so that students could do that day's lab, clean/sanitize their station, and leave in time for the next group of students to arrive. One concern about this is that there might be a traffic flow problem if one lab runs over time. This method would allow schools to accommodate more lab students but with shorter redesigned labs.

(2) Have half of the students come 1 week in person while the other half are online, and switch the next week. This method allows for more communication between group members and reduces the number of students in the class at one time. This also requires students to use physical distancing, masks, and other COVID-related safety. The online students need to actively be paying attention to collect data for their lab partner, looking up missing information from the lab, and providing other support to the students doing the lab in-person.

These methods add no additional cost to schools and serve an equal number of students as normal semesters.

In-person postpandemic

Below we provide three possible ways that students affected by the COVID-19 pandemic could recover the skills lost in the virtual environment. We understand that every institution has different financial, temporal, and spatial constraints. There is no one-size-fits-all solution, and departments and institutions must be creative in their efforts. It is important that during any of the recovery methods, the instructor explain and monitor appropriate use of PPE and follow lab and COVID-19 safety guidelines (https://www.cdc.gov/coronavirus/2019-ncov/community/colleges-universities/considerations.html) (19). Although some PPE and laboratory safety may have been taught at home in a virtual course with the use of videos and/or take-home kits, lack of funding or other logistical challenges may have compromised such efforts.

Laboratory boot camp

We propose that universities could make time to have students attend a laboratory boot camp consisting of perhaps two labs each day to learn the skills that were lost by not attending face-to-face labs. This could take place, for example, in the 1 to 2 weeks before or after the next semester that is deemed safe to be back in-person. In addition, each day could have a different focus, including appropriate handling and disposal of chemicals, how to take appropriate measurements in different circumstances, and the discipline-specific techniques for biology and chemistry. Alternatively, the morning session could be devoted to chemistry application of these techniques, and the afternoon session could be devoted to biology application, or each department can run their own discipline-specific boot camp.

We recommend that students who miss in-person laboratory experiences participate in this boot camp before being allowed to continue in upper-level science courses. While attending the camp, students should be required to keep laboratory notebooks and be assessed to demonstrate competence in core skill development. One way to make this compulsory is to give students incomplete grades in the semester of their online lab classes and then final grades be recorded when their boot camp training is completed satisfactorily. Alternatively, since incomplete grades can affect a student's financial aid, visa status, etc., universities could put an asterisk with a footnote on the transcript stating that in-person lab skill requirements have not been met.

This method requires a limited number of students to return to campus early, thus dormitories would need to open earlier to accommodate those students. Professors would also need to be hired to run these labs and oversee these students. Depending on the number of students that need to take the boot camp, there may need to be multiple sessions. Experienced students could volunteer to aid the boot camp attendees while adding a service-learning entry to their resume.

Club events

We understand that some universities will balk at the idea of requiring students to be on campus before or after the traditional semester. Therefore, we suggest alternative timing. Many universities have a period in the middle of the day devoted to club events when students do not have any classes. We recommend that campus Chemistry Clubs and Biology Clubs could be used throughout the semester to facilitate similar laboratory sessions that are described in the "Laboratory boot camp" section above.

Like in the boot camp, students who plan to take more advanced science courses should be required to attend these laboratory sessions, keep a lab notebook, and be assessed on their skill development, and access to advanced courses could be subject to the completion of these club events.

Professors may need to be hired/compensated to oversee these laboratory sessions. If the number of participating students is more than what can be accommodated during club events, perhaps another period during the day could be arranged.

Triage course

A third option is to design a special laboratory triage course. Students who need to take advanced science classes could be required to take this course to recover all the important laboratory skills. This would not need to be a semester-long course, and could be taken as a co-requisite.

This course should also be required for students needing to recover lost skills and would eliminate the need for students to come to campus outside of the normal semester. Another benefit is that this class could be a component of a professor's course load relieving the need to hire additional faculty.

We recommend that one of the three mechanisms be enforced as a prerequisite or a co-requisite to many upper-level science courses. Finally, the methods prescribed here can be expanded to other STEM courses in which labs proficiencies or other skills have been lost.

CONCLUSION

Students learn more than content in introductory courses, and they respond, like all humans, to more than just the cognitive domain on which educators focus. Beyond the skills imparted in laboratory courses is an unwritten goal of inspiring the next generation of scientists. The first-time students sit down at a microscope to view their own cells on a slide, or the first time they ignite a magnesium strip, can be the very moment when their love of a STEM field is kindled. To that end, we believe that the beauty of science is more difficult to convey online. Watching videos and doing simulated experiments can impart the scientific method, allow for data analysis, and scientific write-up, but are as likely to inspire a love for science as pessimists are to see a glass half full. Putting students back in hands-on laboratory settings will allow us to arouse their latent interests in STEM. When contrasting in-person and online labs, recent studies have shown a significant difference in intellectual accessibility, emotional satisfaction, and anxiety, all of which are better satisfied by in-person labs (20, 21). As described above, virtual laboratories do not adequately prepare our students for upper-level science courses, and more concerning, virtual labs do not prepare this generation of students to become STEM professionals, and we question whether online labs will inspire future STEM leaders.

Over the last decade, there have been suggestions that online lab experiences would be a useful way to save costs (22). Our analysis shows that online labs come up short of developing many proficiencies extracted from AAAS, ACS, and ASM guidelines. Based on this, relying only on remote laboratory experiences would be detrimental for all STEM students' education, and should not be considered except in the transient and uncertain times we are currently in due to the pandemic. All universities should strive to both reinstate face-to-face labs as soon as is deemed safe and backfill the knowledge gaps as much as possible with the remedies that we have proposed.

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