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Designing a Remote, Synchronous, Hands-On General Chemistry Lab Course

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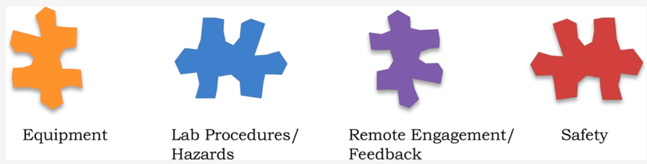
ABSTRACT: The development of a remote, synchronous general chemistry lab course, which was offered to 800 students in the fall semester of 2020, is described. The course was designed with similar curricular goals as our in-person lab course and featured chemistry kits developed by a team of faculty, staff, and graduate TAs. The kits, which were distributed via a rental program through the university bookstore, provided students the opportunity to conduct hands-on experiments at home or in their dorm room. To create the remote lab course, the team negotiated logistical and curricular issues such as finding alternatives to costly precision glassware and instrumentation, adding strategies for engaging students online, decreasing chemical hazards of experiments, and encouraging a safety culture for students working remotely. A professional development graduate course for TA instructors, associated with the general chemistry lab program, was also enhanced by including topics that were relevant for understanding remote learning environments. In redesigning the lab course for remote delivery, we developed new experiments (e.g., calibration), introduced new engagement strategies (e.g., badging), revised several experiments (e.g., heats of reaction), included an Arduino-based spectrometer (e.g., visible spectroscopy and pulse oximetry), and provided new student supports (e.g., TAs on-call). Survey data was gathered to assess student evaluation of the hands-on activities, the presence of synchronous TA help, the badging experience, the value of the lab course, and challenges faced in taking the lab course during a pandemic.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Curriculum, Laboratory Instruction, Distance Learning/Self Instruction, Hands-On Learning/Manipulatives, Internet/Web-Based Learning, Laboratory Management, TA Training/Orientation*

■ INTRODUCTION

In early 2020, the global COVID-19 pandemic altered the pedagogical landscape for in-person lab courses worldwide, forcing many to be delivered remotely. The disruption at the University of Maine occurred midsemester, and when students were sent home, we responded by replacing experimental lab work with previously acquired data sets for students to analyze, supplemented by interactions with TAs online.[1,2] This less-than-optimal learning environment made it hard to engage students and usually meant completely removing the opportunity for doing experiments. While our approach allowed for the completion of the spring semester, the lack of engagement in hands-on experimental work imposed significant restrictions on student learning.

In planning for the fall semester, we weighed the possibility of providing virtual laboratories. Several commercially available virtual packages offer high quality recordings of lab procedures that are suitable for general chemistry. In other approaches, live-streamed lab activities are offered to students.[3] However, while virtual simulations or live streamed experiments can have value, they do not provide the opportunity to develop hands-on expertise in the manipulation of chemicals and equipment.[4,5]

We concluded that, given the likelihood that classes would be remote in the fall, it would be better if we could redesign our first-semester, general chemistry lab course to provide hands-on experimentation and real-time interactions with other students and TAs in a remote modality. Lab kits are available from several commercial vendors, and the development and use of remote chemistry lab kits has been described.[6,7] However, because of the probable limited availability of chemistry kits during a pandemic, as well as their relatively high costs, we decided to make our own lab kits rather than rely on an outside vendor. This paper describes our effort to fit together a number of different "puzzle pieces" as we developed a lab kit in the summer of 2020 and adapted the general chemistry lab course for remote delivery in the fall semester of 2020. Many of the factors we had

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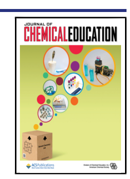

Table 1. Comparison of In-Person and Remote Lab Sequences with Selected Equipment and Chemicals

In-Person		Remote		
Experiments/Activities	Equipment and Chemicals	Experiments/Activities	Equipment and Chemicals	Notes
Policies, Quiz	N/A	Policies, Quiz	N/A	
		Measurement (Calibration badge)	Balance, graduated cylinders; water	New remote lab
Intro to Inquiry	Balance; soda cans, NaOH, NH_4OH, $Cu(NO_3)_2$	Intro to inquiry	Balance, plastic cubes, sucrose, water	Lab was modified
Greenhouse Gases	Gases, hot plate, IR thermometer; N_2,CO_2	N/A	N/A	Not offered remotely
Polymers and Cross-Linking	Funnels; PVA, sodium borate	Polymers and Cross-Linking	Funnels; PVA, sodium borate	
Writing Workshop	N/A	Writing Workshop	N/A	
Synthesis of Alum	Balance, Bunsen burner, volumetric; KOH, H_2SO_4	N/A	N/A	Not offered remotely
Paper Chromatography	Bell jar; $Cu(NO_3)_2$, $Ni(NO_3)_2$, $Fe(NO_3)_3$, $Co(NO_3)_2$, acetone, NH_4OH, dimethylglyoxime	Paper Chromatography	Beakers; dyes: yellow (FD and C5), red (FD and C40), blue (FD and C1)	Lab was modified
Copper Cycle	Bunsen burner; HNO_3, NaOH, H_2SO_4, Zn	N/A	N/A	Not offered remotely
Precipitation and COM	Funnel, ring stand; $AgNO_3$, $CaCl_2$, acetone	Precipitation and COM (Filtration badge)	Balance, graduated cylinders, beakers; $CaCl_2$, Na_2CO_3	Lab was modified
Limiting Reactants	Funnel, ring stand; AgNO3, CaCl2, acetone	N/A	N/A	Not offered remotely
Heats of Solutions	Stirrer, thermometer, balance; HCl, NH_4NO_3, Ca	Heats of Solutions	Coffee cups calorimetry, thermometer; NH_4Cl, $CaCl_2$	Lab was modified
UV−vis Spectroscopy	UV−vis spectrometer; $Cu(NO_3)_2$, $Ni(NO_3)_2$, $Fe(NO_3)_3$, $Co(NO_3)_2$	Visible Spectroscopy (Dilution badge)	Arduino, 3D printed holder, PCB; blue dye (FD and C1), water	Lab was modified
		Exploration of Pulse Oximetry	Arduino, 3D printed holder, PCB	New remote lab

to consider, such as safety, equity in access to materials and supplies, engaging students, and motivating them to be accountable for their learning in a remote environment, were faced by other chemistry programs, as is well-described in the recent special issue of this *Journal*.[8−15] Our motivation for describing our approach and discussing the outcomes is to provide information that may be beneficial for anyone seeking to do something similar, if not now, then sometime in the future.

■ TRANSITIONING FROM IN-PERSON TO REMOTE LABORATORIES

Baseline In-Person Lab Course

The learning objectives for the general chemistry lab course focus on helping students understand how to use the scientific process to make careful observations in a laboratory setting as they learn to manipulate scientific equipment, handle chemicals safely, analyze chemical results, formulate representations using data, develop claims based on evidence and analysis, and communicate results. Our goal in developing a remote lab course was to preserve these learning objectives to the extent possible given the constraints imposed by students working remotely. The in-person course includes some "traditional" lab experiments, such as the synthesis of alum, the copper cycle, and measuring the heats of reaction. We also offer a series of inquiry experiments, some of which have been reported previously in this *Journal*, including an experiment on greenhouse gases and a polymers and cross-linking experiment, which incorporates the **CORE** approach (**C**hemical **O**bservation, **R**epresentation, and **E**xperimentation).[16−18] The left side of Table 1 lists typical experiments and activities for our standard in-person lab course, along with a list of selected equipment and chemicals. The features of the redesigned remote lab course are shown on the right side of Table 1 and are discussed in detail in the following sections.

Overview of Design of Remote Learning Activities

Our overall strategy in reconceptualizing the course was to consider a variety of factors that would impact the implementation of a remote lab, such as the sequence and timing of experiments; establishing a weekly routine; the availability of chemicals and supplies; selection of less- or nonhazardous chemicals; enhancing student engagement; and the connection of activities to our curricular goals. Virtual lab rooms were established to help provide structure for remote learning. During the first week of the semester, students met online with TAs in their assigned virtual lab room to go over course materials (syllabus, policies), provide instructions for how to obtain a lab kit, establish a routine of what would happen every week online, and discuss norms for the course. A calibration activity was included early in the semester to introduce students to the importance of making careful measurements and to develop an understanding about the limitations imposed by the substitution of standard laboratory equipment such as analytical balances and volumetric glassware with inexpensive "pocket" or kitchen scales and plasticware in the lab kits.

Another concept introduced for the remote lab course was digital badging.[19,20] Badging was introduced in the first lab experiment for two reasons: to enhance student engagement with the remote lab work and to give students opportunities to gain competency in certain lab skills that are important for the first semester lab course, such as mass and volume measurements, filtration, and dilution of solutions. In addition, the video uploaded as part of the badging process provided TAs with an opportunity to observe each of their students at work. This latter feature proved to be especially useful since some students did not turn their cameras on during the lab session. We included two more opportunities (three in total, see Table 1) in the semester to earn digital badges in filtration and solution dilution because we knew that these were skills that students had

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difficulty with during the regular in-person laboratories. Students earned points for digital badges with each badge worth no more than 50% of the grade for an experiment.

Several of the experiments that used hazardous chemicals or specialized equipment needed to be replaced by experiments students could do safely in their home. For example, in the introduction to inquiry experiment performed at the beginning of the semester for the in-person lab course, students conduct qualitative experiments to explore the concept of density and chemical reactivity. This experiment employs chemicals (strong bases and transition metal salts) and other items (a variety of soda cans) that we chose not to include in the lab kits. So, a new introduction to inquiry experiment was developed for the lab kit that allows students to explore density by using concentrated sucrose solutions and small plastic cubes. Similar considerations (as well as our short development window) led to the removal of the copper cycle, greenhouse gases, and alum synthesis lab experiments. Finally, several experiments in our in-person lab course use UV−vis and FTIR spectrophotometers. Since we wanted to retain an experiment on spectroscopy for the remote laboratories, we developed an Arduino-based, home-built, visible spectrometer.

Lab development was carried out in parallel by teams of 2−3 TAs working on different experiments, with the whole effort coordinated by faculty and staff. Online meetings were held where each team reported on their progress and discussed problems that needed to be addressed. A Google doc was set up with a running list of considerations that could impact the feasibility of an approach, including such factors as identifying alternative chemicals that could be handled safely in a nonlab environment and would not pose any hazards for shipping; considering whether a student could do the experiment alone in a several hour time frame (students have lab partners for many of our in-person lab experiments, which are three hours long); the type of equipment needed; the underlying chemical concepts associated with an activity; and the precision and accuracy of data that could be acquired. An added benefit of these discussions was they resulted in some chemicals and equipment being used in more than one activity. Finally, outside of this development, we also worked with a computer scientist to design a visible spectrometer device that students could use for two purposes: measuring absorbance as a function of concentration to construct a Beer's Law plot and measuring the ratio of absorbances at two wavelengths to explore the science involved in pulse oximetry, which helped to introduce a connection to the pandemic since the measurement of blood oxygen levels as an indicator of health was very much in the news.

The student lab procedures and rubrics for written reports were constructed after an experiment was considered feasible and workable. Last minute adjustments in procedures were sometimes required if delays in shipments of chemicals or equipment were encountered (which happened more than once!). This introduced some fluidity in the curricular development process that went well into the fall semester. It was necessary to develop a procedure to provide students with additional items for their kits as supplies became available.

Assembling the Lab Kits

Near the end of the summer, a team of TAs, staff and faculty began the process of creating the lab kits. It took several weeks of work for about 10 people to assemble all the materials and pack everything into boxes, which were then sealed and delivered to the university bookstore for distribution. The lab kits contained all the chemicals, equipment, and disposable items required for each lab (see the Supporting Information for a complete list). This provided equal access to all students since some would be living on campus in the dorms without easy access to a kitchen and others might not have the means to purchase items from a store. The only thing that students had to provide was tap water. The university bookstore delivered the kits via a rental program which that also included the cost of shipping to return the kits at the end of the semester. The rental cost of each kit was $50. Students who were on campus or in the area picked up their kits at the bookstore; the rest were mailed out. The contents of the kit were approved for mailing by the university safety and environmental officer, and students signed a safety contract prior to beginning the lab. At the end of the semester, students were instructed as to which items they were required to return and how to package the kits. They had the option to dispose of chemicals (which were nonhazardous and safe to put in the trash or down the drain) and paper products or they could return everything in the box.

Remote Supports Created: Virtual Lab Rooms and TAs On-Call

In transitioning to remote learning, our organizing principle was that students would start all lab activities synchronously with a TA on Zoom at the time associated with a student's scheduled lab section. Due to social distancing policies that were in put in place during the pandemic, students did not work in pairs as they typically do during a regular in-person lab. To promote a feeling of being connected with their peers and the TA, and to help give structure to remote learning, we introduced the concept of virtual lab rooms. This allowed us to organize online learning in a way that paralleled in-person laboratories. Each fall semester, we typically offer about 50 lab sections/week with 16 students per lab. Each lab section is associated with a specific, physical lab room, and multiple lab sections meet in that room throughout the week. To preserve the fall semester schedule and mirror the idea of physical rooms to virtual space, each student was assigned to a virtual lab room and one Zoom link was created for each virtual lab room. If students were unable to attend lab during their assigned time, they could consult the lab schedule and find another lab session with the same Zoom link offered at another time during the week. This permitted a small number of students who missed a particular lab (through sickness, athletic events, etc.) to make up their lab on a different day (Note: There were 16 students in each virtual lab section and the decision to allow a student to do a "make-up" lab in another section was entirely the TAs; any TA could decline allowing additional students for any reason. In practice, TAs welcomed most students seeking make ups in this way).

In anticipation that our graduate TAs might get sick, we also created a system for back-ups. Each TA was assigned to several lab sections as the primary TA as well as being designated a TA on-call. This meant that, on any lab day, when multiple lab sections were operating simultaneously, there would be at least one (and sometimes up to three) TAs on-call. An on-call TA's responsibility was to be available in case the regularly assigned TA got sick. On-call TAs could do other tasks, but they were instructed to keep their schedule open to be able to respond quickly if needed. This system worked remarkably well, even when 3−4 TAs (out of 20) were unavailable during some weeks.

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a.

Mass of Empty Graduated Cylinder (g)	Measurements of the 25 mL Graduated Cylinder				
	Estimated Volume (mL)	Mass of water & cylinder (g)	Mass of Water (g)	Ave. Mass of Water (g)	Calibrated volumne (mL) using density (1.0 g/mL)
17	5	21.9	4.9	4.87	4.87
		21.9	4.9		
		21.9	4.8		
	10	26.8	9.8	9.77	9.77
		26.7	9.7		
		26.8	9.8		
	15	31.5	14.5	14.60	14.60
		31.7	14.7		
		31.6	14.6		
	20	36.6	19.6	19.60	19.60
		36.7	19.7		
		36.5	19.5		
	25	41.5	24.5	24.63	24.63
		41.7	24.7		
		41.7	24.7		

b.

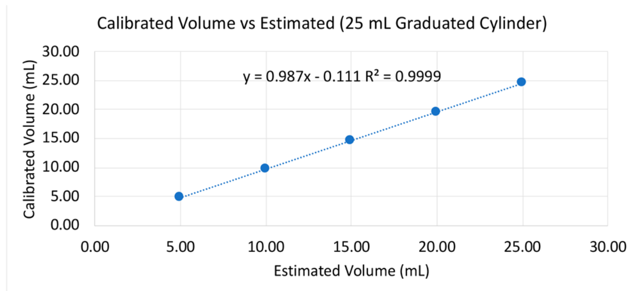

Figure 1. Measurement experiment. Sample data from submitted student work: (a) calibration table and (b) calibration graph. See the Supporting Information (Figure S1) for additional information related to this experiment.

In-Person Supports Transitioned to the Remote Learning Environment

Several years ago, a 1-credit course was created to provide professional learning for TAs. In this course, graduate TAs meet once a week with the faculty in charge of the general chemistry lab program to discuss active learning strategies for facilitating lab work, develop strategies for working together as a team of instructors to provide students with consistent feedback, and foster awareness of fairness, equity, diversity, and respect. In planning our transition to a remote learning environment, we knew it would be important to incorporate discussions about online learning in this graduate TA course. Thus new assignments were developed, for example, to read and discuss excerpts from the book *Small Teaching Online*,[21] view video presentations regarding our assumptions about college students,[22] how some students can struggle online with technology,[23] and how to assess lab skills remotely.[19] We also covered the next generation of science standards and wait time.[24]

One of the professional learning activities that occurred in a prior semester of this graduate course revealed the difficulty that many TAs had in scoring student lab work consistently across multiple lab sections.[25] An important outcome of this activity was the development of rubrics for lab reports as resources for students and guides for TAs. When rubrics were added to our lab report procedures, we also created a lab report writing workshop, which was given early in the semester. Prior to the workshop, students prepare a draft lab report for an experiment they conducted in the previous week. They were instructed to follow a rubric and use a lab report template, which was available as a Word file that contains styles, sections, and examples similar to a journal template. During the workshop, TAs lead a discussion with their students about what information belongs in each section, how to present and analyze data, and what constitutes a strong claim. In the remote setting, breakout rooms on Zoom were used to allow small groups of students to discuss each section. We justified replacing a lab experiment with a writing workshop for both the in-person and remote versions of the lab course because writing scientific reports can be difficult for many students. An additional benefit of the workshop is that it helps to set consistent expectations concerning quality and due dates among students and TAs across multiple lab sections.

■ REMOTE LABORATORY EXPERIMENTS AND ACTIVITIES

There is a body of literature that describes the history, role, and purpose of chemistry laboratories, some of which even questions the value of lab work.[26−31] Our purpose in writing this paper is not to justify the lab activities in terms of meeting specific learning objectives but rather to provide an overview of the remote lab course we developed so that the reader will be able to use this information to make comparisons with their own experiences with other general chemistry lab courses. It is important to point out that our in-person lab course has 12 experiments/activities while the remote lab had 10. Offering fewer experiments in the remote lab semester allowed us to build in some flexibility in the schedule, which students could use to catch up with their work. The following section briefly describes the experiments and activities that were included in the remote lab course.

Experiment/Activity #1: First Remote Meeting, Safety, Course Policies, Quiz, and Online Norms

Prior to the start of classes, all students enrolled in the general chemistry I lab course received an email containing a Zoom link for their virtual lab room and informing them that the first lab session would provide important information to orient them to the remote lab course. During the initial session, TAs introduced themselves, provided their contact information, discussed the remote lab routine, online norms, how to obtain the lab kit and check for any missing items, create an online account, get extra help, etc. All TAs were asked to develop a structured routine for students in their lab sessions. For example, it was recommended that the first 20 or 30 min of each remote lab session be devoted to students arriving and asking questions. For experiments that had prelab assignments, TAs would ask students at the beginning of the lab to indicate through a private chat whether they had completed the assignment. This was done as part of a strategy to shift the responsibility of preparing for lab to students, as well as to reduce the administrative burden on TAs to assess submitted work prior to each lab activity. Students were required to submit their written prelab assignment when they submitted the postlab assignment. Lab sessions were not recorded.

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Experiment/Activity #2: Introduction to Measurement and Calibrating Volumetric Equipment

In the second experiment/activity, students calibrated the plastic graduated cylinders in their lab by measuring the masses of different volumes of water and constructing calibration graphs for each cylinder. Figure 1 The purpose of this lab was to help students understand the idea of precision in scientific measurements. This was an important activity since the calibrated labware would be used in other experiments throughout the semester. To highlight the importance of this activity and to create additional engagement, we included the opportunity to earn a digital badge, which has been successfully used with youth organizations[32] and more recently in chemistry to help students achieve competency in lab skills.[19,20] Students were instructed to make a short (approximately 5 min) video to demonstrate their knowledge of the calibration process, including graphing their data. They were provided with a rubric that explained the elements they needed to include in their video (e.g., stating their name, lab section, and showing certain steps). To earn a calibration badge, students uploaded their videos to a private link (only seen by their TAs) and they also submitted their tables and calibration graphs (see Figure 1 for student table and calibration graph). Students were required to earn a certain score on the rubric, which included an assessment of the video and quality of their data (tables and graphs). Students were not required to obtain a precise or accurate value, rather the emphasis was on the process. They had an opportunity to resubmit work if some elements were missing. The submission of videos also provided TAs an opportunity to see individual students and observe in more detail what they were doing remotely. Our assumption was that this would create more engagement and connection between students and the TAs.

Promoting a Safety Culture Starting with Experiments/Activities #1 and #2

The course was designed with the understanding that students would conduct lab experiments in a wide variety of settings (e.g., home, dorm room, etc.). Lab experiments were developed using nonhazardous or less hazardous chemicals that would meet the learning objectives for the course. Since students would be working in a nonlab setting, it was important for them to establish a safety culture for their own environment. In the first assignment, students took a quiz that included questions about safety policies, which were described in a section in the syllabus called Remote Lab Safety Policies and Information (see the Supporting Information). In the second assignment, students created an emergency safety plan that included the location and description of where they would perform laboratories, who they would inform when they were performing lab experiments, and how to seek medical help. Although the calibration activity was a "safe" lab experiment, we used it as an opportunity for students to establish a habit of practicing safe lab work. Students were instructed to perform this experiment on an absorbent pad placed on a clean, well-lighted, flat surface, wearing goggles and gloves. In subsequent assignments, students were required to construct safety tables from safety data sheets as part of their prelab assignment (which was handed in post lab). Students were encouraged to turn on their cameras while they were in the "virtual" lab room. TAs were also permitted to ask students to turn on their cameras if they had any concerns about safety. This helped TAs feel more connected to the activities occurring remotely and was critically important in promoting careful experimentation and a safe, remote activity.

Experiment/Activity #3: Introduction to Inquiry

In this experiment, students explored the concept of density by investigating whether several, different sized clear plastic cubes were made from the same or different materials. Students first calculated the density of the cubes by using the digital balance and a ruler to measure the mass and volume of each cube (Note that, due to the lower precision (0.1 g) of the digital balance, students needed to weigh two of the smaller plastic cubes at the same time and calculate the mass of one from the average). Then, they prepared a 48 wt % sucrose solution (d = 1.219 g/mL), by using their calibrated graduated cylinders, digital balance, packets of table sugar (included in the lab kits), and tap water (assuming d = 1.0 g/mL). They tested whether the plastic cubes floated or sank in the sucrose solution. Students were provided with a table of densities of concentrated sucrose solutions, but they were not told the identity of the plastic cubes. In actuality, the cubes (TAP plastics) were all acrylic plastic, d = 1.18 g/mL, which sinks in a 40 wt % (1.17 g/mL) sucrose solution and floats at 44 wt % (1.20 g/mL).[33] Thus. if they prepared the initial 48 wt % solution correctly, they observed the cubes floating on the sucrose solution.

The next part of the experiment focused on designing experiments to gather evidence to support a claim about whether the plastic cubes were made of the same material. An additional curricular goal in this experiment was to introduce the idea that experimental procedures influence results, i.e., the instruments used influence accuracy, as does the skill in making measurements. Students were instructed to design an experiment to gradually lower the wt % sucrose solution, until they observed the cubes sinking. This was followed by designing an experiment to add additional sucrose until the cubes floated again. The objective of these experimental steps was to bracket the density of the material being tested. Students were encouraged to develop their own ideas about how to design the experiments and justify their procedures. A sample student calculation for the cube density is shown in Figure 2.

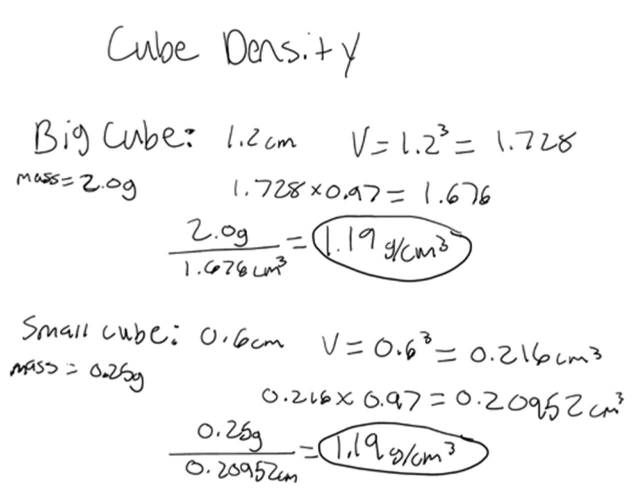

Figure 2. Introduction to inquiry experiment. Calculation submitted by a student from post lab submission. See the Supporting Information (Figure S2) for additional information related to this experiment.

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Experiment/Activity #4: Polymers and Cross-Linking Experiment

In this experiment, students prepare slime and explore the influence of cross-linking on polymer properties. The experiment incorporates the **CORE** approach (**C**hemical **O**bservation, **R**epresentation, and **E**xperimentation), which was reported in *JCE* several years ago.[17,18] In the three-phase **CORE** learning cycle, students are guided through chemical observations while they consider a series of open-ended questions (phase 1), they apply analogical thinking to develop ideas about representations (guided by an "analog and target" worksheet in phase 2), and they consider the representation as they design and conduct experiments to explore a phenomenon (in phase 3). In this experiment, slime is prepared by mixing solutions of poly(vinyl alcohol) and sodium borate, which were deemed safe to include in our lab kits. The equipment needed was also readily obtainable for the lab kits. Therefore, the experimental procedure for the remote lab was very similar to the procedure used for our in-person laboratories. Table 2 shows a student example of the Analog and Target worksheet filled out during phase 2.

Experiment/Activity #5: Workshop for Writing Lab Reports

Students write a draft lab report for the Polymer and Cross-Linking experiment to use in this activity. Information about the purpose of this workshop and how the activity is facilitated by a TA is presented in the section on In-Person Supports Transitioned to the Remote Learning Environment (vide supra).

Experiment/Activity #6: Paper Chromatography

The paper chromatography experiment used for our in-person laboratories involves the use of transition metal ions, ammonium hydroxide, acetone, and dimethylglyoxime. For the remote lab, we revised the experiment to use various food dyes and saline solutions for elution. Although the chemicals used were different, the concepts of migration and separation of chemicals on paper, R_f values, and identification of an unknown mixture were covered in a similar manner as our in-person lab experiment. Figure 3 shows student chromatograms.

Experiment/Activity #7: Precipitation and COM (Filtration badge)

This is another example of an experiment that required the selection of alternative chemicals that could be safely shipped and handled by students working remotely. The in-person lab uses silver nitrate and calcium chloride. To explore the concept of the conversation of mass in the remote lab experiment, silver nitrate was substituted by sodium carbonate. Students prepared solutions of $CaCl_2$ and Na_2CO_3, which were mixed to form $CaCO_3$, filtered, dried, and weighed. This experiment was another opportunity for students to demonstrate a lab skill and earn a digital badge in filtration. The rubric for the precipitation badge is shown in Table 3.

Experiment/Activity #8: Heats of Solutions

For the remote lab experiment, we revised a classic "coffee cup" calorimetry experiment to replace calcium metal, HCl, and NH_4NO_3 with less hazardous chemicals. In the remote lab experiment, students measured the heat of solution for an exothermic ($CaCl_2$) and endothermic (NH_4Cl) process. The procedure involved adding the salt to a known mass of water in a nested coffee cup, closing the lid, gently swirling the coffee cup to mix the solution, and recording the temperature as a function of time. Since students were working on their own (i.e., without

Table 2. Filled out Student Analog and Target Worksheet Completed during Phase 2

Analog and Target Comparison	Silver Paper Clip Chains Compared to Polyvinyl Alcohol	Black Paper Clips Compared to Sodium Borate	Action of Linking Silver Chains with Black Paper Clips Compared to the Chemical Reaction	Product of Linking Silver Chains Together with Black Paper Clips Compared to the Slime Product
Similarities: What characteristic does the analog share with the target?	Each silver clip representing a monomer of a polymer is similar to how actual polymers function. They act as individual compounds in long chains.	Each black paper clip represents the sodium borate as a cross-linker, demonstrating how it is its own compound.	The process of attaching the black paper clips to the silver chains demonstrates the concept of cross-linkers binding polymers together to form the new polymer (slime in this case).	The final product of the analogy accurately demonstrates how the combination of the polymers with cross-linkers forms a new polymer compound.
Differences: What features of the analog (paper clip model) do not represent the target?	However, the paper clip model does not accurately depict how polymers are made up of multiple molecules binding to form one polymer.	The paper clip model is not accurate in representing how sodium borate is made of separate molecules binding together to form one cross-linker.	The paper clip model is not accurate in demonstrating how those bonds actually form. As it does not show which molecule bonds with which.	The analogy does not represent how the target texture differs from two reactant textures. It also does not accurately represent how the target (slime) behaves as a new polymer.
Differences: What features of the target are missing from the analog (paper clip model)?	The idea of those separate molecules are missing from the paper clip model, as the paper clip just represents the polymer as a compound, not as the individual parts of the polyvinyl alcohol polymer (CH_2, CH, and OH).	The individual molecules of that target are what is missing from the analogy of the paper clip model.	The bonds between the individual parts of polymers and the individual parts of the cross-linkers are missing from the analogy. Such as the CH of polyvinyl alcohol binding with the OH of sodium borate.	The texture of the target is missing from the analogy. The analogy shows that the individual polymers and cross-linkers have the same paper clip "texture" which is accurate, but when it is formed it still retains that paper clip "texture" where the target has a whole new texture of being a semisolid (Newtonian fluid) which is different from the polymer and cross-linker being in liquid form. The analog also does not represent how the slime behaves as a new polymer. The slime behaves as more of a solid than liquid in comparison to the two liquid reactants. While the analog represents each part (reactants and slime product) as solid paperclips that behave the same when moved.

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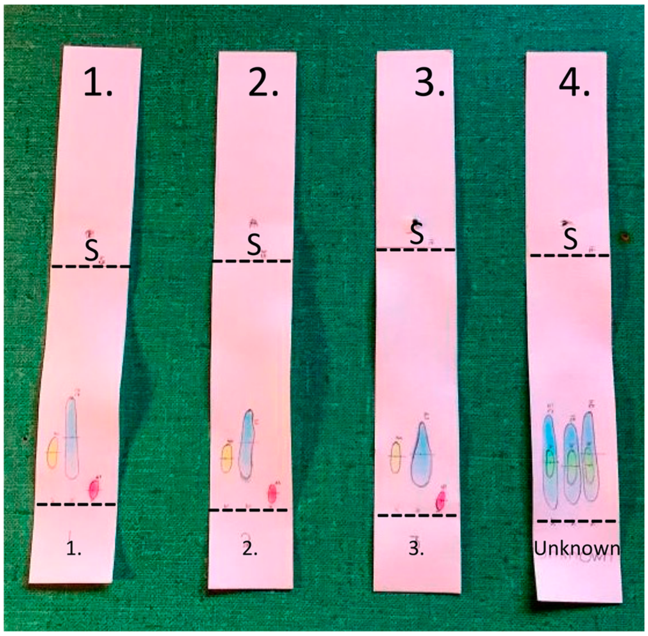

Figure 3. Paper chromatography. Annotated student data from the paper chromatography experiment. Strips labeled at the top 1−3 are three trials each spotted with yellow, blue, and red dyes. Calculated R_f values were 0.20 (yellow), 0.25 (blue), and 0.39 (red) on the basis of the averages of three runs. The strip labeled 4 at the top contains three trials of an unknown sample that show blue and green spots. The green spot is the overlap of yellow and blue dyes. Dotted line near bottom indicates the original position of spots at the beginning of the experiment, while the higher dotted line indicates the solvent front at the end of the experiment. See the Supporting Information (Figure S3) for additional information related to this experiment.

a lab partner), they were encouraged to do a couple of practice runs before collecting data. Figure 4 shows a graph from one of the runs of heats of solution for $CaCl_2$. From this student's lab report, the calculation quantities for ΔH_{soln} were 16 ± 1.5 kJ/mol for NH_4Cl and $\Delta H_{soln} = -70 \pm 10$ kJ/mol for $CaCl_2$. This is then 20% difference in each case from the reported values of ≈ +14 kJ/mol for NH_4Cl and ≈ −82 kJ/mol for $CaCl_2$.

Experiment/Activity #9: Visible Spectroscopy Experiment (Dilution badge)

Designs for simple, student-built spectrometers have been reviewed recently in this *Journal*, including options that are suitable for remote learning.[34] Our goal was to provide a spectrometer that required very little assembly on the student's

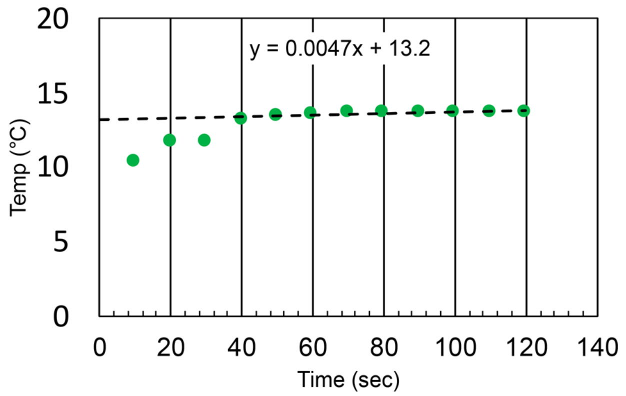

Figure 4. Heats of solution. Graph of student data for the heats of solution for $CaCl_2$.

part and did not depend on students providing any components, such as a smart phone camera for colorimetry. The spectrometer was also designed so that it could be used for two purposes: measuring the absorbance of a series of solutions at a single wavelength and as a simple (uncalibrated) pulse oximeter, which is based on a ratio of absorbance at two wavelengths.

The objective of this experiment was 2-fold: to introduce students to spectroscopy and to provide an opportunity to practice the skill of dilution. A dual wavelength (660 and 940 nm) Arduino-based device and a 3D printed cuvette holder were developed (see the Supporting Information for additional details). A 1.0 mM solution of blue dye (FD and C1) was provided in the lab kit, which students used as a stock solution to make a series of dilutions. Students prepared solutions with different concentrations by the dilution of the stock solution. They used the Arduino-based spectrometer to measure the absorbance of each solution at 660 nm. Each measurement was repeated three times, and the data was tabulated and graphed as illustrated in Figure 5. A dilution badge was awarded to students who successfully demonstrated the process of dilution and explained how the Beer's law graph was constructed.

Experiment/Activity #10: Exploration of Pulse Oximetry

Pulse oximetry, which measures the oxygen levels in arterial blood, is based on the ratio of the absorbance of oxygenated and deoxygenated hemoglobin. In the final experiment of the semester, students explored the concept of pulse oximetry by using the Arduino-based spectrometer. This was designed to include a SunLED (XZM2MRTNI45SC2C) component that has two LEDs, at 660 and 940 nm, which can be controlled independently (The device was not calibrated and students

Table 3. Instructions and Rubric for Filtration Digital Badge

Criteria	Performance Description and Score	
	1	0
Introduction:	Face can be seen; state name and lab section.	Step is absent
Introduction of precipitation reaction:	Include the names of chemicals used in the precipitation reaction. Show the chemical equation for the reaction, including phases of all chemicals.	Step is absent
Details of reaction:	State concentrations and volumes of each solution used and mix the solutions to show the formation of the precipitate.	Step is absent
Setting up to filter:	Show and describe how a piece of filter paper is folded, torn, weighed, and placed into a filter funnel.	Step is absent
Filtering:	Show and describe how a solution containing a precipitate is poured into a funnel containing filter paper.	Step is absent
After Filtering:	Show and describe the solution draining through the filter paper in the funnel. You do not need to video the entire process.	Step is absent
Collection of precipitate:	Explain how the mass of the precipitate was determined (i.e., after the filter paper was air-dried and weighed). You do not need to show this, just explain in words.	Step is absent

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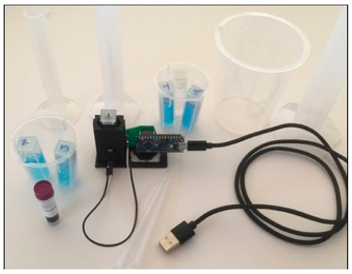
a.



b.

Solution	Conc. (μM)	Abs.
1	8	0.29
2	16	0.53
3	24	0.77
4	32	0.95
5	40	1.1

c.

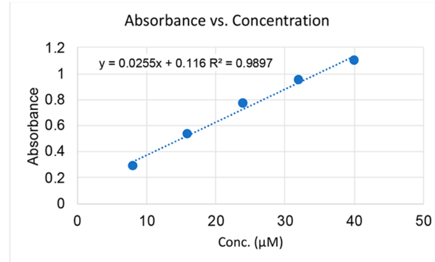


Figure 5. Introduction to spectroscopy. (a) Visible spectrometer, which includes an Arduino (computer), dual wavelength LED, sensor, printed circuit board, jumper cables, a USB cable to connect to a computer, and a 3D printed cuvette holder. (b) Student data table for the absorbance of the blue dye at 660 nm. (c) Beer's law plot of the data.

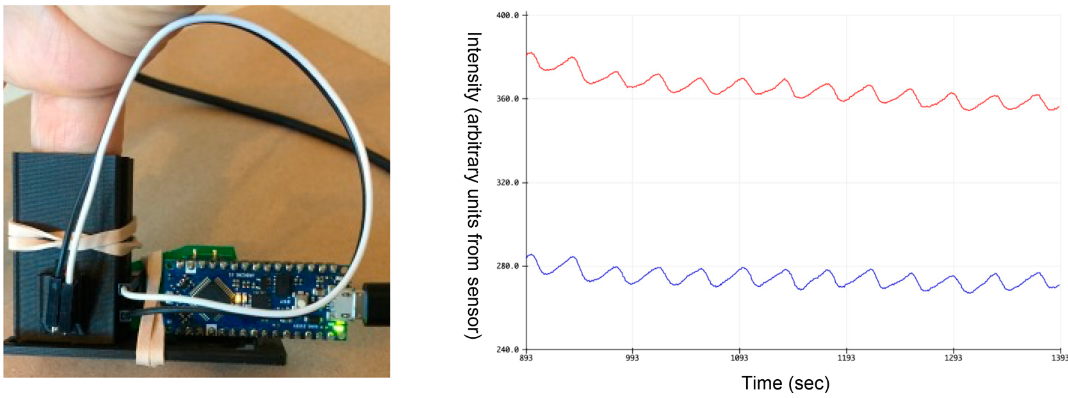


Figure 6. Exploration of pulse oximetry. Photograph showing finger inserted in the holder with the LED light source connected to the Arduino (left), and sample intensity signal from finger (*y* axis) at 940 (blue line) and 660 nm (red line) over time (right).

were cautioned that it was not possible to use it to measure oxygen levels precisely). Students used their finger as the "sample". The 3D printed part used in the visible spectroscopy experiment was constructed to hold a standard 1 cm cuvette, and it was designed to expand to accommodate a finger. A photo of the setup is shown in Figure 6 (left), and the type of output is illustrated in Figure 6 (right). The sinusoidal waves indicate a regular pulse, and the ratio of absorbance of oxygenated (940 nm) and deoxygenated hemoglobin (660 nm) is measured at the same point in each cycle. The lab procedure included a link to a video describing the basis for the oximetry measurement (https://www.youtube.com/watch?v=4pZZ5AEEmek). As this was the last experiment of the semester, this lab was presented as an exploration and students were not required to make any quantitative measurements. If students were unable to get a good signal, they were sent data (similar to Figure 6 (right)) to help them understand pulse oximetry.

■ STUDENT SURVEY

Student Survey Context

In the fall of 2020, an IRB approved survey was administered online to 760 students enrolled in the general chemistry lab course, and 574 students (76%) granted permission to use their data. The survey was made available before the Thanksgiving break, after which all students living on campus returned home to complete the semester. This allowed for the sampling of students' experiences while they still had reliable access to technology. However, a limitation of this assessment strategy is that the experiments on spectroscopy and pulse oximetry, which occurred in the last 2 weeks of the semester, are not well represented in the survey responses. The survey included three multiple choice questions, followed by a series of five open ended textbox questions. At the beginning of the survey, students were informed that their individual responses would not be seen by their TAs, would have no influence on their grade, and that the data for each question would be aggregated, without identifying names or lab sections. For the analysis of the text questions, a grounded theory approach was taken, conducted by a single researcher (MB), allowing for categories to emerge from student responses.[35,36] The primary idea expressed in each written response was used to code the response into a category. Some categories eventually were combined, and some categories involving infrequent responses (e.g., only 1 or 2 students) have been excluded from the summary described in the next section. Additional examples are provided in the Supporting Information.

Student Survey Results: Multiple Choice Responses

Three multiple choice questions were asked at the beginning of the survey to obtain a snapshot of students' views about the hands-on activities, the help offered by TAs, and an overall assessment of the remote lab course. While the student survey was optional, nearly all of the students provided some answers (96%). The data for 550 students shown in Figures 7−9 indicate favorable views of the remote laboratories. In response to the question, "how important were the hands-on activities of the lab for helping you understand chemistry?", 80% of students thought it was moderately to very important while only 4% of students thought it was not important (Figure 7). Similarly, 80% thought it was moderately to very important to have TAs available synchronously when conducting laboratories remotely,

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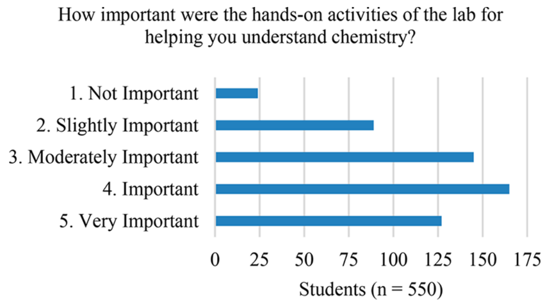

Figure 7. Importance of hands-on activities. Student responses to the prompt: How important were the hands-on activities of the lab for helping you understand chemistry? (n = 550 students).

while 5% thought it was not important (Figure 8). The third multiple choice question about whether students would

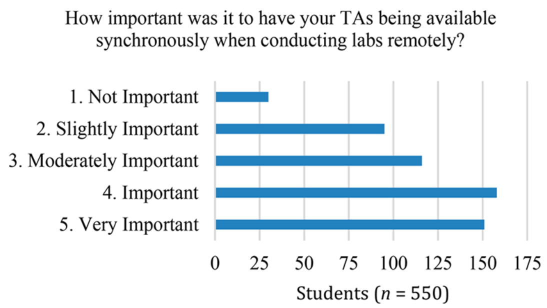

Figure 8. Importance of TAs being available synchronously. Student responses to the prompt: "How important was it to have your TAs being available synchronously when conducting labs remotely?" (n = 550 students).

recommend this remote lab course to another student was included as a proxy for an overall opinion of the course. Approximately 61% would recommend or strongly recommend the course, 23% were undecided, while 1 in 5 (17%) would not recommend it (Figure 9).

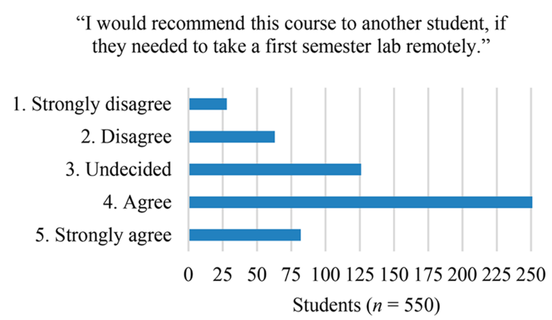

Figure 9. Student recommendations about the lab course. Student responses to the prompt: "What is your opinion about the following statement: 'I would recommend this course to another student, if they needed to take a first semester lab remotely.'" (n = 550 students).

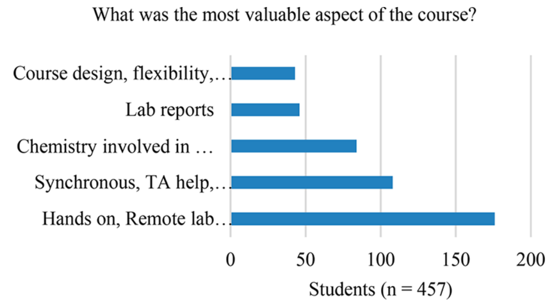

Figure 10. Valuable aspects in the lab course. Categories of student responses to the following prompt: What was the most valuable aspect of the course? (n = 457).

Open Ended Textbox Responses

Valuable Aspects of the Lab Course. Students were asked to respond to the prompt "what was the most valuable aspect of the course?". These responses were sorted into five categories as shown in Figure 10. Over a third of the students mentioned the hands-on/remote nature of the course in discussing the opportunity of being able to engage in lab work remotely and how hands-on activities assisted their learning. Almost 1 in 4 students mentioned the positive impact of having synchronous lab sessions occur where TA help was available, permitting real-time trouble shooting and discussions with other students and the TA. Students also mentioned the value of being exposed to chemistry concepts in the lab course, e.g., the connection between class and lab concepts, the use of analogical reasoning, a focus on what occurs at the molecular level, learning to use data without being explicitly told what to do with it, and the process of gaining chemical insight. Students also mentioned valuable aspects of the lab reports, including the lab report writing workshop, drafting reports, and analyzing data. Finally, students also mentioned aspects of the structure of the course (e.g., course design) such as the weekly online sessions, flexibility in turning in assignments, the ability to practice skills, and be able to produce videos independently. Selected student comments in each of these categories are shown below.

Students finding value in the hands-on, remote nature of the lab:

> *"The most valuable aspect was actually doing hands-on stuff. I'm a very hands-on learner. I have to do problems repeatedly or perform experiments in order to really learn so this online schooling has really hit me hard. This class did its best to help with that and I'm really grateful."*
>
> *"What I valued most was being able to practice as if it were a real lab setting even though this year it was not."*

Students finding value in synchronous lab session with TA help:

> *"I would say the most valuable aspect of this course is the fact that we are able to conduct labs synchronously rather than asynchronously because then we would be confused as to what to do without the TAs help."*
>
> *"Since it was synchronous it made a HUGE difference. My other chem class is asynchronous and I can't stand learning chemistry by myself it is unbearable."*

Students finding value in the chemistry involved in the course:

> *"The most valuable aspect of the course was conducting different types of experiments with different chemicals because it helped to visualize and enhance my understanding of chemical interactions."*
>
> *"I think that the most valuable aspect of the course was the analogical models that were introduced to us in some of the laboratories. They were very helpful in linking and explaining ideas that I was not confident with in a situation where we could not be in person."*

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"The most valuable aspect of this course is understanding how models can be used to represent and help understand processes."

Students finding value in the lab reports:

"I think the most valuable aspect of this course was having the lab report workshop. It helped to have a time in the beginning of the semester where we could get questions answered before writing a lot of our reports. Especially since the lab was remote it was nice to have a set time for questions."

"I think the lab reports were the most valuable part of the course. For the most part, the lab procedures were very easy to follow, but when we had to complete the lab reports we had to stop and think about the chemistry behind the experiment."

Students finding value in course design:

"I enjoyed doing the laboratories by ourselves. They were very independent and made me feel like I was in control the entire time."

"The structure of lab time"

"I most valued the hands-on aspects of it and being able to do the laboratories by myself instead of with partners as I prefer working alone."

Badging Experience. Most students (62%) had a positive or very positive view of the badging experience (Figure 11; n = 463). The data supports the idea that, for a majority of students, badging was an effective strategy to better connect remote students to other students, TAs, and the lab experiments. There were also two types of negative comments: some students thought that the badging was not beneficial to their learning (22%), while some students thought that having to practice and produce a video about a lab skill was boring or tedious (8%). Sample student comments are shown below Figure 11.

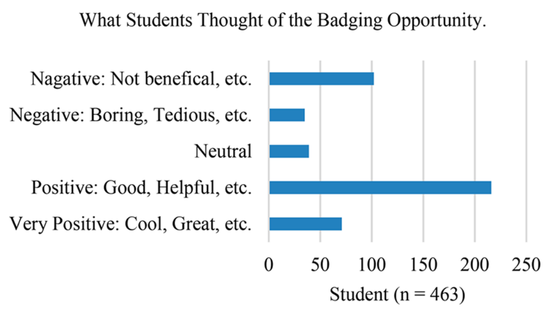

Figure 11. Badging experience. This lab involved earning badges to demonstrate lab skills. Student responses to the prompt: "What did you think of this opportunity?" (n = 463).

Students finding the badging opportunity was not beneficial:

"The badges didn't really mean anything to me because I had to complete the experiment either way."

Students finding the badging opportunity was boring or tedious:

"While it was an interesting semester doing lab remote, the learning badges were kind of tedious in the sense of recording yourself doing a lab and explaining what was happening to the camera. Also, it is awkward to do so."

Students who were neutral about the badging experience:

"I think every opportunity to learn in important. I'm thankful that this course was available to take at home this semester given our current conditions."

Students who were positive about the badging experience:

"I acknowledge that the badges represented integral skills that anyone in a lab must have, and I appreciate the dedicated focus to developing these."

Students who were very positive about the badging experience:

"I find this feature very unique and helpful in the sense that the video/badges are separate from the assignment. I find the badges particularly useful for the student because they have to explain in words to another person how to complete the lab themselves and why the lab behaves the way it does. Not to ramble on, but I also find the recording aspect very new, inspiring, and fun in a way."

Student Challenges. Students were asked about the challenges they faced taking the course and these responses are summarized in Figure 12. Nearly half of all students identified challenges related to two aspects of the course: technology and space issues. In terms of technology, power outages, slow and dropped Internet connections, computer issues, issues with Zoom, making videos, and uploading assignments were mentioned. Finding adequate space to do the laboratories was also a challenge for students, especially for students living in the dorms. Adequate space was an issue occasionally for students living at home, e.g., finding a quiet place to work was difficult. Some students wrote about not having any specific challenges. An issue for some students was related to the course being online, such as doing the laboratories alone, i.e., without partners. Several students wrote about the feeling of isolation of doing a lab alone or the difficulty in doing some experiments that required them to do something like stirring a solution and recording the time simultaneously. Scheduling was a challenge for some students related to having to follow a schedule or keeping track of what was happening and the stresses this caused. Finally, missing materials or picking up items in the lab kit were a challenge for some students. Sample student comments are shown below.

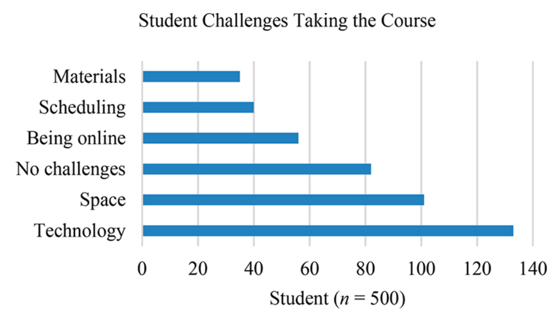

Figure 12. Challenges students faced. Student responses to the prompt: "What, if any challenges, did you face taking the course (e.g., computer, access, Wi-Fi, scheduling, living situation)? Please help us understand your challenges." (n = 500).

Students with technology challenges:

"Wifi was a huge issue. There would be days we lost power or reception so I really struggled making sure I was at labs. But mainly it was hard to make sure I had all materials and understood what everything was and how they were intended to be used."

Students with space challenges:

"Living situation and space was definitely a struggle. My roommate was always in the room and my desk was way too small to do full experiments on."

Students without challenges:

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"I had to move home in the middle of the semester temporarily, but thankfully having the lab remote actually allowed me to take everything with me and stay caught up in the course."

Students with challenges related to being online:

"The biggest challenge for this course was, not surprisingly, not being able to complete these labs in person, with other people. Completing the labs online and so forth was not too big of an issue, but it is much preferable to complete labs in person (although there isn't much of a choice this year).

Students with challenges related to scheduling:

"Finding time to write the lab reports was difficult. I enjoyed the labs, and I understood them well enough to write the lab reports, but finding time to write the reports on top of all other class work was extremely difficult for me."

Students with challenges related to kit materials:

"My only challenge was getting the correct supplies for the lab and having to coordinate getting any missing supplies; I feel as though it went rather smoothly but it was obviously more difficult getting these supplies than showing up to a class that already had the supplies within it."

CONCLUSIONS

The significant team effort to adapt and develop experiments for our first semester general chemistry laboratories resulted in our ability to offer a synchronous, remote, hands-on lab course for 800 students in the fall of 2020. The experiments and activities selected for the remote lab included the calibration of labware, digital badging, polymers, a writing workshop, paper chromatography, precipitation and conservation of mass, heats of reaction, visible spectroscopy, and pulse oximetry. In adapting the lab course for a remote modality, careful consideration was given to meeting curricular goals while balancing the cost and availability of equipment, chemical safety, and the organizational framework for delivery of the course. Survey assessment data suggest a very successful first semester lab course for most students, in terms of providing hands-on experiments and interactions with TAs and other students online. However, the data also suggest that, for some students, the remote lab experience was difficult or did not meet expectations for a laboratory experience. There were also issues encountered by some of our students in terms of their technological skills or the availability and consistency of Internet connections.

The level of chemical sophistication of the experiments selected for this lab course was limited by the lack of more sophisticated, precision equipment as well as restrictions on the chemicals that could be safely shipped. Because of this, we have not used a similar approach for a second semester general chemistry lab course, opting instead to do laboratories every other week in-person with half the number of students, to conform to the reduced COVID-19 capacities of lab spaces. As time goes on, more creative solutions may present themselves, so we cannot rule out additional, more-advanced lab experimentation being developed for remote laboratories.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00559.

Information about kit contents, student dashboard, Arduino spectroscopy, additional student survey examples, safety information, and thumbnail pictures and figures of additional information related to the measurement, inquiry, and chromatography experiments (PDF, DOCX)

PCB-3D-ArduinoSoftware with files used for PCB design, 3D printed part, and Arduino software (ZIP)

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Notes

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