

Experiences Implementing Hands-On Wet-Lab Experiments Designed for Supervised At-Home Use During the Pandemic

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Abstract In this work we discuss our experience implementing six hands-on wet-lab experiments designed specifically for at-home use during the pandemic. The experiments cover the concepts of classification of compounds, limiting reagents, spectrophotometry, equilibrium constants, and osmotic pressure. Student survey data on a method of presentation of the experiments using two cameras, and on the effectiveness of demonstration videos of the experimental techniques, which could be viewed by students asynchronously, are presented and discussed. Also discussed are considerations of cost and logistics in the development of hands-on at-home wet-laboratory experiments, and the potential importance of simulations or videos to complement them.

Keywords: *undergraduate curriculum, laboratory instruction, hands-on learning, aqueous solution chemistry, conductivity, equilibrium, laboratory equipment, spectroscopy*

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1. Introduction

The sudden transition to remote learning due to the COVID-19 pandemic has necessitated the development of some form of laboratory curriculum that can be delivered remotely. Prior to the pandemic there had been many excellent suggestions for at-home experiments to be used in a distance education format (unsupervised and asynchronous). [1,2] With the sudden transition to remote learning being widespread, and largely conducted synchronously through digital meeting platforms, the body of students and the potential modes to deliver the curriculum have become much broader, though the ability to provide hands-on laboratory experiences has been limited by the high cost of commercial hands-on chemistry kits, and the limited time for the development of economical alternatives. [3] This has led to many faculty feeling dissatisfied with the quality of the curriculum provided during the pandemic. [4] In this work we present the approach taken at Nassau Community College of developing hands-on wet-lab experiments that can be performed safely by students at home with supervision via a digital meeting platform. The cost of the experiments presented in this work is a fraction of the cost of commercial chemistry kits that provide hands-on wet-lab experiments.

One obstacle in the implementation of this curriculum in a cost-effective manner has been the logistics of distributing and recovering the chemistry kits used by students. At our institution the kits have been provided to the students at no additional cost. The kits were paid for primarily using emergency funds that were made available due to the pandemic. However, if the kits were not recovered the emergency funds were not adequate to sustain the use of the kits, nor was our normal operating budget. We discuss here several approaches that we have taken for distribution and recovery of the kits based upon the level of pandemic restrictions.

Another obstacle in the implementation of these experiments has been presenting them effectively through a digital meeting platform. In this work we present data on the effectiveness of an approach using a top-view camera to demonstrate techniques, display the proper physical setup of equipment and present written material. We also investigated the effectiveness of making videos available that demonstrated aspects of the experimental procedures before they were performed. Data we present suggests these are both very beneficial to students learning in a remote setting.

2. Materials and Methods

Students were provided with a chemistry kit consisting of the following items:

1 conductivity sensor (made in house, described below)

1 power supply with alligator clips (3-volt)
 1 LED (12-volt)
 100 mL plastic graduated cylinder
 250 mL separatory funnel
 1 vial containing 100 strips of Blue Litmus paper
 1 vial containing 100 strips of Red Litmus paper
 3 × 120 mL screw lid containers
 1 digital scale (0.01 g)
 10 plastic centrifuge tubes (15 mL)
 16 large paper cups
 4 small paper cups
 16 painter's filters
 16 coffee filters
 3 plastic eyedroppers
 1 squirt bottle
 1 plastic weighing boat
 1 mortar and pestle
 24 interlocking plastic blocks (1 ¼ × 5/8 inch)
 1 interlocking plastic block baseplate (5 × 10-inch)
 5.5 ft of dialysis tubing (precut into 6-inch lengths)
 1 microfiber rag
 2 × 500 mL bottles of distilled drinking water
 30 grams calcium chloride dihydrate
 10 grams of magnesium sulfate heptahydrate
 1.0 gram of citric acid
 2.5 grams of calcium sulfate
 1.0 gram of arginine
 1.0 gram of sodium chloride
 30 grams of sucrose
 100 mL of canola oil
 10 mL of triethyl citrate
 100 mL of a sports drink
 15 mL of 1.0 % acetic acid
 0.50 mL of green food coloring
 9 light filters (made in house, described below)
 1 LED flashlight (100 lumen)
 5 AAA batteries
 2 plastic cuvettes

In addition to the items in the kit that was provided to them, the students themselves were required to provide:

a small pot
 a coffee mug
 a pair of scissors
 ice
 a smartphone

Students were also required to have access to a sink with hot and cold running water and to have a dedicated work area in view of their camera where samples could be left undisturbed to dry or equilibrate.

2.1. Construction of Equipment Made in House

A number of excellent conductivity apparatus have been described previously. [5,6,7,8] The design used in these experiments is shown in Figure 1. It was settled upon based on its simplicity, making it amenable to the necessity that a large number of them be constructed by our technical assistants. Additionally, it is compact enough that it can be used to test a solution in a 15 mL centrifuge tube and is easily assembled and disassembled in order to troubleshoot it. This device is sensitive enough to detect a higher level of electrolyte impurities in our local tap water than in the distilled bottled water provided in the kit.

The light filters used were of our own design and were constructed in-house. They were created from combinations of inexpensive plastic-colored films used in stage lighting. The spectra of the full set of filters, normalized to a maximum transmittance of 1.0 is shown in Figure 2. Details on the construction of the conductivity apparatus and the light filters are provided in the supporting files.

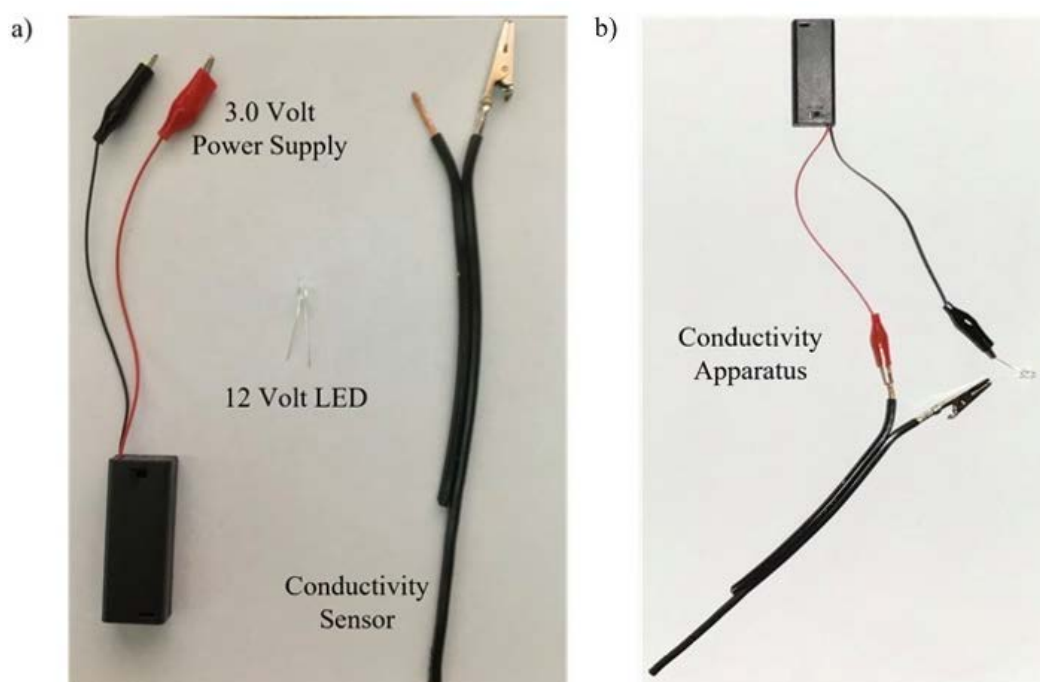


Figure 1. a) Components of the conductivity apparatus b) Assembled conductivity apparatus

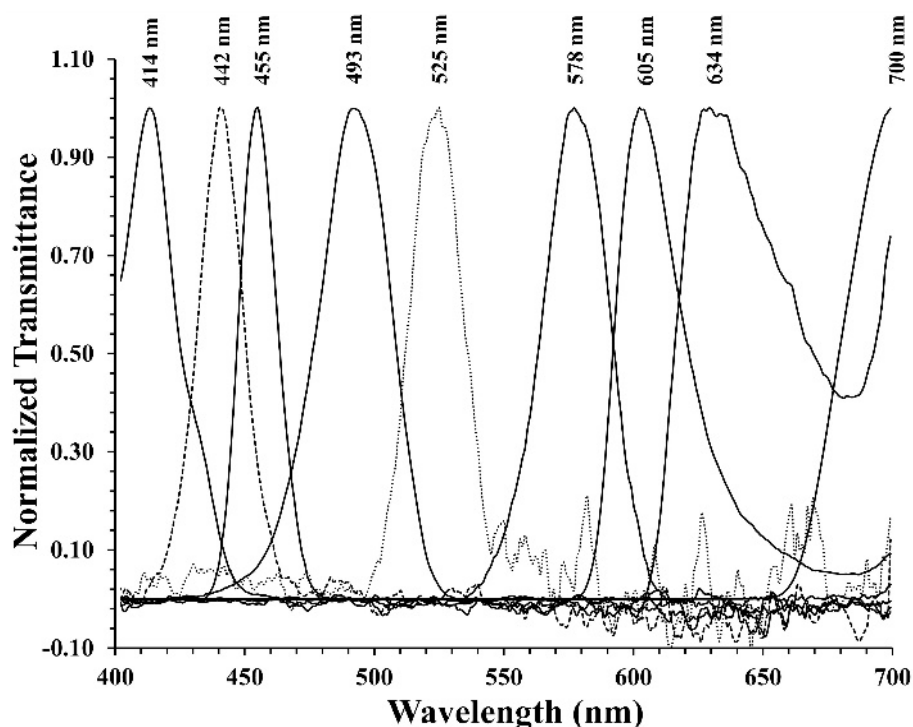


Figure 2. Normalized transmittance spectra of filters used in the experiment “Building a spectrophotometer and using it to measure an absorption spectrum”

2.2. Safety Hazards

Safety was a primary consideration in the development of these experiments. Cuts from sharps or broken glassware and burns are the two most common injuries sustained in chemistry laboratories. [9] None of the procedures discussed here calls for any potentially dangerous sharp objects or an open flame, a spark, or a heat source, other than hot tap water. All the chemicals used are either food substances or ones that the American Food and Drug Administration has categorized as Generally Recognized as Safe for use as a food additive or ingredient. None of the chemicals are classified as corrosive or flammable at the concentrations provided to the students. None of the experiments produced waste requiring special disposal considerations. All the waste could safely be washed down the sink or disposed of in the trash. All the chemicals can be shipped via private carriers (except those prohibiting the shipment of liquids) with no special considerations with respect to packaging or disclosure, other than the requirement that they are labeled clearly with chemical names, and that all the SDS sheets be enclosed. Our department maintained the same safety requirements, that students wear goggles and a laboratory coat, when performing these experiments. These experiments have been performed at our institution by 523 students without any reported safety incidents.

2.3. Mode of Delivery of the Course Content

In a traditional face-to-face laboratory setting instructors can effortlessly switch between writing on a chalkboard and demonstrating a technique or displaying the proper physical setup of equipment. In the remote setting a deliberate effort must be made to seamlessly perform these same actions. Our approach to addressing

this problem has been to use two cameras in presenting and supervising these experiments. When just speaking to the class, a single camera directed at the instructor’s face was used, but when writing on paper to show how to perform calculations, demonstrating techniques, or displaying the proper physical setup of equipment, a second camera providing a top view of the bench was used instead (Figure 3). In this mode the top view occupies most of the screen for the students, but the first camera focused on the instructor still appears in a small box in the upper right-hand corner. One major difficulty reported by instructors when teaching through a digital meeting platform is in presenting handwritten work on a whiteboard. [10] Using the top-view camera in the manner described here allows instructors to write directly on paper and have it occupy a large portion of the screen for clear viewing by students. This aspect of teaching through a digital meeting platform we have found so effective that we have adopted it not just for remote laboratories, but also to conduct simultaneous remote and face-to-face lectures. For students attending the lecture face-to-face they view the instructor’s slides and handwritten work projected on a screen in the classroom as the instructor conducts and records the class through a digital meeting platform. Students that are quarantined or otherwise absent can attend the lecture remotely or view a recording of it asynchronously. The use of the top-view camera is also in many ways superior to a face-to-face laboratory demonstration. By use of the top-view camera all the students can always have an unobstructed view of the instructor’s benchtop. Additionally, being able to quickly raise or lower the camera allows the instructor to easily switch from showing their whole benchtop to focusing on a data table or single line in the procedure. By bringing the camera very close to the surface of the benchtop the magnification achieved allows incredible detail to be

shown, such as the meniscus of a liquid, the markings on a measurement device, or the shape of small crystals. Views this close cannot be shared in a traditional face-to-face demonstration.

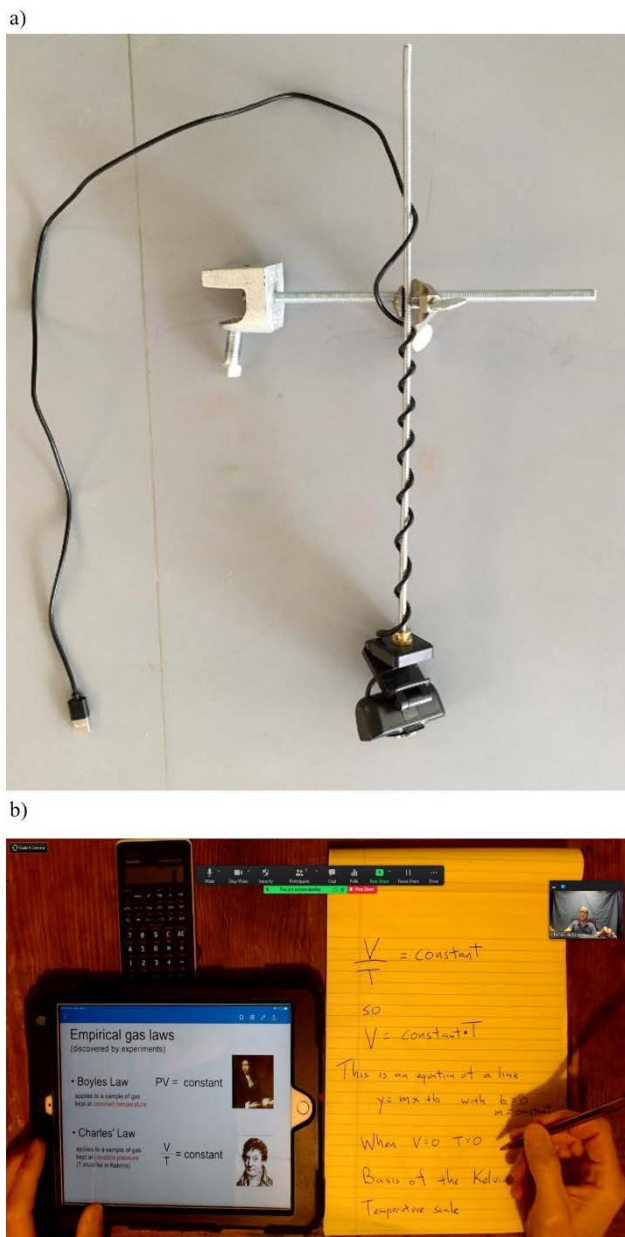


Figure 3. a) Top-view camera with mount b) View of benchtop as seen by students through the top-view camera

For all the experiments described here videos demonstrating critical portions of the procedure or discussing concepts related to the experiments were produced and made available to students as resources to be used before class as pre-laboratory preparation, or after class when preparing their reports. These videos were a particularly valuable resource to students that were occasionally unable to attend class due to COVID-19 related, or other short-term difficulties. At our institution both before and during the pandemic we have not offered laboratory courses in an asynchronous distance education format, though we did allow a small number of asynchronous makeup labs. Performance of these labs was greatly assisted by these demonstration videos, along with the video of the class meeting itself.

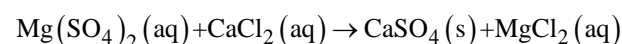
2.4. Synopsis of the Experiments

2.4.1. Classification of Compounds Based on Conductivity, Solubility, and Litmus Testing

In this experiment students classify five compounds: sucrose, magnesium sulfate, arginine, citric acid and calcium sulfate. In Part I of this experiment, students attempt to dissolve 1.0-gram of each compound in increasing volumes of water to determine the compound's solubility classification (very soluble, freely soluble, soluble, etc.). In Part II students compare the conductivity of the solutions prepared in Part I, to standard solutions (1.0 % sodium chloride, 1.0 % acetic acid and distilled water) in order to classify the compounds as strong electrolytes, weak electrolytes or non-electrolytes. In Part III of this experiment students use red and blue litmus paper to test the solutions they prepared in Part I. Using the data from all three parts of the experiment students classify each of the compounds as either a: strong acid, strong base, salt, weak acid, weak base, soluble non-electrolyte, or a compound of undetermined classification due to its very low solubility.

2.4.2. Graphical Study of the Limiting Reagent Effect

In this experiment students study the precipitation reaction:



Students prepare stock solutions of both calcium chloride (~7.3 M, saturated) and magnesium sulfate (~0.36 M). The same volume of magnesium sulfate stock solution (7.0 mL) is placed in ten 15-mL centrifuge tubes. Calcium chloride stock solution is added to each of these tubes in amounts that vary from 5 drops to 7 mL. After mixing and allowing the reaction to come to equilibrium, the contents of each tube is filtered through a pre-weighed coffee filter. The filtrate is washed several times with water to remove the soluble product and unreacted reactants. The filters are then hung to dry for a week. After drying, the filters are weighed and a graph of Mass of CaSO_4 obtained versus Number of Drops of Calcium Chloride added is prepared. The limiting reagent is magnesium sulfate for all but the first few trials, so if the samples are adequately washed and thoroughly dried this graph will display a very clear pattern of increasing for the first few trials with the smallest amounts of calcium chloride added and then leveling off due to the magnesium sulfate becoming the limiting reagent.

2.4.3. Building a Spectrophotometer and Using It to Measure an Absorption Spectrum

Many excellent spectrophotometry experiments for at-home use have been already described. [11,12,13,14] The idea for the spectrophotometer used in this experiment was similar to one described previously [15] in that it used interlocking plastic blocks, though rather than using a diffraction grating as the monochromator we used the set of light filters described in *Materials and Methods*, and the camera of a smartphone was used as the light detector. The spectrophotometer students construct is shown in Figure 4. The interlocking plastic-block baseplate is immobilized to the tabletop with double-stick

tape. The position of the flashlight varies based upon the filter being used, so after it has been aligned with a particular filter it is taped down to immobilize it. The light intensities are measured using a free app (Color Assist Lite for Apple Users and Color Grab for Android Users) that reports RGB values. Students read either the R, G or B value based upon the wavelength of the filter they are using. The solution students measure the spectrum of is a dilute solution of green food coloring. Data collected on the same solution, using both a commercial spectrophotometer and the interlocking plastic-block spectrophotometer, is shown in Figure 5.

2.4.4. Determination of the Canola Oil-water Partition Coefficient of Triethyl Citrate by Refractometry

Students prepare two sets of standard solutions containing 0-10% (m/m) triethyl citrate. One set is prepared in canola oil and the other in water. The refraction of each of these standard solutions is measured using a handheld refractometer. This data is used to create two calibration curves: Refraction versus Percent Triethyl Citrate in Water, and Refraction versus Percent Triethyl Citrate in Canola Oil. A mixture of canola oil, water, and triethyl citrate is also prepared and the refraction of

samples of the equilibrated canola oil and water layers are each determined. The percentages of triethyl citrate in both the equilibrated canola oil and water layers are determined graphically from the calibration curves. The mass/mass percentages obtained from the calibration curves are used along with the densities of water and canola oil to calculate mass/volume percentages and then the partition coefficient.

2.4.5. Determination of the Temperature Dependence of the Solubility Product of Calcium Sulfate

Students prepare saturated solutions of calcium sulfate in hot tap water, room temperature water and ice water, from pre-measured masses of calcium sulfate. After allowing the mixtures to equilibrate, each is filtered through a pre-weighed coffee filter. After allowing the filter to air dry for a week, the masses of undissolved calcium sulfate are determined by weighing the filters. From this data the masses, moles and equilibrium molarities of dissolved calcium sulfate are all calculated. Using an ICE table the K_{sp} is calculated at all the three temperatures. Finally, students prepare a van't Hoff plot to determine the standard enthalpy and entropy of the reaction.

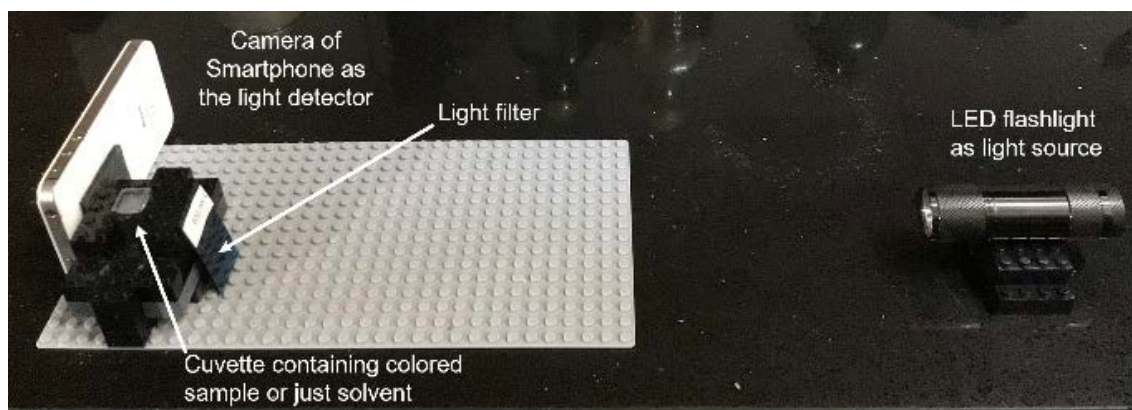


Figure 4. Interlocking plastic-block spectrophotometer used in the experiment “Building a spectrophotometer and using it to measure an absorption spectrum”

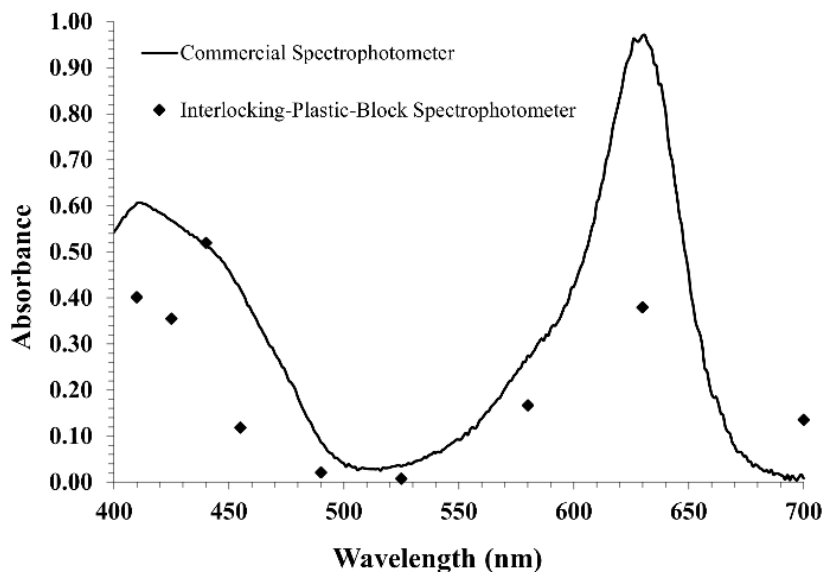


Figure 5. Absorbance spectrum of dilute green food coloring measured on a commercial spectrophotometer and data collected using an interlocking plastic block spectrophotometer

2.4.6. Determination of the Osmotic Pressure of a Sports Drink

Students prepare a series of 11 solutions of known percentage of sucrose (m/m) varying from 0-10%. They also prepare 11 “balloons” of a sports drink in dialysis tubing sealed with knots at each end. The sports drink “balloons” are each dried with a microfiber rag and weighed. Each is then incubated in a different sucrose solution for 30 minutes. After the incubation period they are removed from the sucrose solutions, dried, and weighed again. A graph of *Change in Mass versus Percentage of Sucrose* is prepared and the percentage that is isotonic to the sports drink is determined graphically by interpolating the percentage of sucrose that would result in zero change in mass. That percentage is converted into a molarity of sucrose, and the osmotic pressure of the isotonic sucrose solution and, therefore that of the sports drink is calculated.

2.5. Cost and Logistics

The process used for preparing, distributing, and having students return the kits throughout the seven semesters that the kits have been used due to pandemic restrictions varying. In the spring and summer of 2020 our technical assistants assembled the kits and shipped them to students with prepaid return shipping labels. This approach was unsustainable because it was too labor intensive at our level of staffing, the rate of return was only about 75%, and students packing their own kits for return resulted in substantial leakage and breakage. In the fall 2020 semester due to loosening of pandemic restrictions we were permitted to conduct a check-in period as the first lab meeting, where students came to campus in small groups and assembled their own kits on an assembly line, which our technical assistants had set up. At the end of the semester, students were asked to return the kits by driving up to a designated outdoor drop-off area. Only a few students were unable to drop off in person, and they were accommodated by making shipping arrangements. This approach for assembly and return was much more sustainable because it greatly reduced the preparation time for our technical assistants, it saved a great deal on shipping costs, resulted in much less leakage and breakage, and it improved the rate of return to almost 100%. In addition, these kits now already assembled, were used for the spring 2021 semester by just adding the consumable items and shipping them to students (face-to-face check-in was not permitted at our institution in the spring 2021 semester).

The cost for all the materials required to perform these six experiments including both reusable and expendable items was \$57.18/student. The expendable items only accounted for \$6.69/student of this cost though. Shipping of a complete kit was \$8.03 each way. So, while running this sort of program requires a substantial infrastructure investment in the reusable equipment, the cost to sustain it is a small fraction of the cost of the reusable equipment and shipping. If it can be arranged that students can pick up and/or drop the kits off rather than requiring shipping, the sustained costs are even smaller. If these total costs are still beyond budget limitations, five of the six experiments

presented here could be done for about half the total cost mentioned above, since the separatory funnels and refractometers, which are used in a single experiment, account for more than \$25/student.

Most of the materials were purchased retail as needed, since wholesale minimum quantities were impractically large. The refractometers, separatory funnels, graduated cylinders, digital thermometers, scales, cuvettes, and litmus paper were all purchased wholesale because the savings for these items was substantial, and the minimum purchase volume was not unreasonable considering our foreseeable needs and storage space. All these items were ordered from overseas wholesalers with a recommended eight-week lead time, and all were delivered within that time frame. A detailed summary of the costs for all materials for these six experiments and the vendors used are in the supporting files.

3. Results

In the summer of 2021 three sections were surveyed concerning the effectiveness of the top-view camera and the demonstration videos. The results are summarized in Figure 6. Students overwhelmingly found the use of the top-view camera an effective instructional approach, with only 2% of the students rating it as inferior to a face-to-face demonstration of laboratory techniques. The videos demonstrating the experimental techniques were also overwhelmingly seen as effective by students, with 95% of the students describing them as helpful.

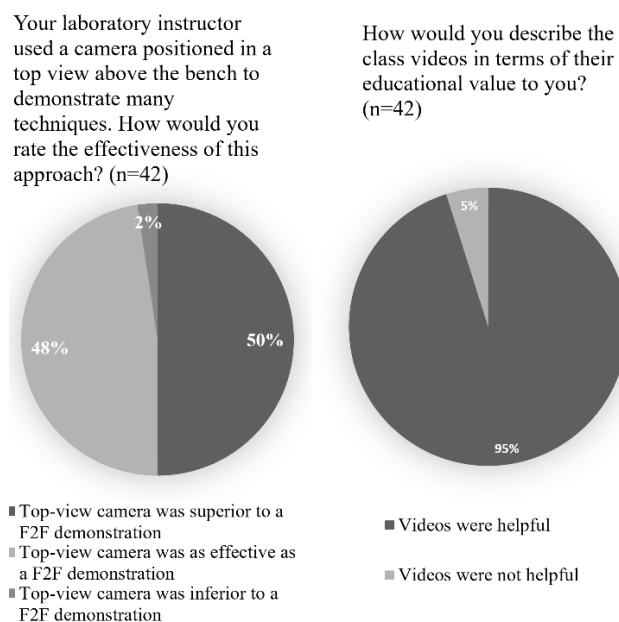


Figure 6. Results of student surveys concerning effectiveness of the top-view camera and the educational value of the videos in demonstrating experimental techniques

4. Discussion

The pandemic has created an unprecedented challenge for the development of laboratory curriculum that can be delivered remotely. There may be many factors besides

the loss of hand-on laboratory work that have negatively impacted student's remote learning during the pandemic, such as the loss of peer interaction and increased cognitive load [16] but the transition to a remote learning format by virtually every institution teaching laboratory science raises the stakes on a question that has been considered in the chemical education community for a long time, about how to precisely define the value of traditional hands-on laboratory work. [17] Despite the time-honored belief that its value is self-evident, data on its pedagogic value is ambiguous, or at least unsatisfyingly clear, in establishing that it is essential. [18] We agree that the pedagogic basis of traditional hands-on laboratory work should be studied and defined more precisely as other authors have suggested [19,20], but until that occurs, we also believe the viewpoint, that traditional hands-on laboratory work is essential, should be the basis of curriculum developed. We think this viewpoint is well expressed in the American Chemical Society policy statement on the "Importance of hands-on laboratory science". [21] While the experiments presented here do meet the description of being hands-on laboratory science, as educators our primary concern with their continued use is that these experiments have replaced exposure to traditional experiences, with alternate activities designed to be performed safely at home. As educators we do not see an alternative approach that is financially feasible that could replicate many types of traditional experiences in a hands-on remote format. We would like to suggest that a combination of hands-on experiments suitable for at-home use, along with simulations [22,23] videos or other modes of delivery, which have been selected to complement the deficiencies these experiments have in providing exposure to traditional laboratory experiences, would be an effective approach to satisfying the ACS policy statement.

5. Conclusion

The experiments described here have served the educational needs of our students effectively through the pandemic and we have received nothing but positive feedback about them from students. If remote laboratory learning continues at our institution using hands-on at-home wet labs with kits, the use of top-view cameras will be recommended for all lab instructors. The top-view camera will also be used to conduct simultaneous face-to-face and remote lectures. If remote laboratory instruction does continue at our institution, the approach that is most sustainable, from the standpoint of cost and logistics, will be to request that students come to campus to assemble and return their kits, if at all possible. Concerning the value of hands-on laboratory science, we believe traditional face-to-face laboratory experiences have many learning goals that cannot be replicated remotely by any approach, but that hands-on wet labs designed to be performed at home, such as those presented here, complemented with simulations or videos selected to expose students to unique aspects of traditional face-to-face laboratory science, may be an effective approach to meeting the ACS policy statement when teaching remotely.

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Statement of Competing Interests

The author has no competing interests

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