ONLINE TEACHING OF A LAB COURSE AMID A PANDEMIC — A CHALLENGE AND AN OPPORTUNITY

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INTRODUCTION

In Spring 2020 the coronavirus pandemic led to the widespread adoption of social distancing, meaning that nearly all in-person classes were moved to online sections.[1, 2] This change in the teaching delivery method significantly affected all disciplines.[3-6] The impact on a particular class could be slight or significant, depending on the nature of the class.[7] In our opinion, the greatest challenge is the engineering lab courses. First, the lab courses give students an opportunity to become familiar with specific equipment and its operation. Students learn the fundamental concepts of equipment operation in lecture classes. In the lab the main objective is to apply this knowledge and operate the equipment.[8-10] This is particularly true in engineering lab courses[11-14] such as the Chemical Engineering Unit Operations Lab course, which is the focus of this paper. The second reason is that this lab course provides students with instruction and practice to improve their communication skills and teamwork. In the lab class we require small groups of students to work on a specific experiment and prepare a group report.

Both factors – being familiar with the equipment/operation and improving communication skills – are evaluated in the chemical engineering (ChE) lab courses, making online teaching very challenging. However, online teaching could be an opportunity to develop new methods for future chemical engineering education, not only amid a pandemic or other disruptions, but also for future distance learning environments. With many universities offering parts of their curriculum online to attract both international and domestic distance education students, it is thus timely to discuss the strategy of offering distance learning alternatives to purely hands-on experiments for an engineering lab course. In this paper we discuss the efforts and outcomes from a hybrid mode of teaching the Chemical Engineering Unit Operations junior level lab course offered at the University of Oklahoma (OU) during Spring 2020 amid the Covid-19 pandemic.

Because of the rapid increase in the number of infections in our state as well as in the country, we were presented with the unprecedented situation of making a decision on how to quickly modify our teaching approach. Other universities around the country faced the same challenge. The OU campus was closed right after spring break in March 2020, and all the courses were transferred to an online format, including the lab course. This essentially cut the class into two parts. The first part (before the campus closed) was conducted as traditional in-person teaching, while the remaining portion had to be continued without students' personal presence in the lab. To mitigate the negative impact on the students' learning and educational experience, we decided to leverage in-person experiments completed in the first half semester and develop a deep dive online course for the remaining part of the semester. In the following section, we will discuss our approach and both the positive and negative impacts of this transition.

STRUCTURE OF THE UNIT OPERATIONS CLASS

We first provide some general information for the Chemical Engineering Unit Operations Laboratory course at OU. Similar to corresponding courses at other universities, the objectives of this course are as follows:

1. Apply principles developed in chemical engineering courses to the analysis of specific chemical engineering equipment and unit operations.
2. Design experiments and analyze results using appropriate calculations and statistical methods.
3. Be aware of and articulate potential personal safety concerns and operate equipment in a safe manner.

4. Develop and improve skills in communicating technical information both in oral and written formats.
5. Develop skills necessary for group work — interpersonal skills, coordination of the efforts of several persons, leader and subordinate roles.

In addition to the course outcomes, according to the ABET standards for student outcomes, we also use this course to assess the following requirements:[15]

- **Student Outcome 3:** An ability to communicate effectively with a range of audiences
- **Student Outcome 5:** An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
- **Student Outcome 6:** An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

The course is divided into four-to-six sections depending on the enrollment. Each section of the course meets once per week, with the lab session lasting four hours. There are typically 4-5 student groups in each section with each group consisting of 3-4 students. Each group would normally perform five of the six available experiments during the semester (Figure 1). The students are evaluated based on written reports, short oral quizzes, oral presentations, and peer evaluations. The grading rubrics for each of the student activities emphasize a fundamental understanding of the underlying chemical engineering principles, the ability to design and analyze experiments, teamwork, and the ability to communicate effectively, that mirror the course objectives and ABET student outcomes. Like many of our colleagues who made the switch to online teaching, we now faced new challenges of how to continue evaluating these specific aspects of student work and how to continue to enrich the students' experience and knowledge of ChE unit operations.[16-18]

Experiments

I: Steam Condensation on a Single Tube
II: Shell and Tube Heat Exchangers
III: Membrane Gas Separation
IV: Fluid Flow Characteristics/Tray Hydraulics
V: Vapor Flow Rate Effects Distillation at Total Reflux
VI: Gas Absorption in a Packed Tower

Order of Experiments

Group	First Experiment	Second Experiment	Third Experiment		Fourth Experiment	Fifth Experiment
A	I	III	IV	Spring Break	II	V
B	III	II	V		IV	VI
C	II	IV	VI		V	I
D	IV	V	I		VI	II
E	VI	I	II		III	IV

Figure 1. *The original schedule of experiments for the in-person class. In this section there are five groups, each of which is assigned five out of six available experiments during the semester.*

ONLINE COURSE FORMAT

Before spring break, each group had performed the first three experiment periods, which means that for each of these experiments, there were groups who had already completed them and other groups who had not. For example, Group A of the section depicted in Figure 1 had carried out all experimental work on Experiment I (Steam Condensation on a Single Tube), Experiment III (Membrane Gas Separation), and Experiment IV (Fluid Flow Characteristics/Tray Hydraulics). Group A was scheduled to next carry out Experiment II (Shell and Tube Heat Exchangers) and finally Experiment V (Vapor Flow Rate Effects Distillation at Total Reflux). At that point in the semester, those two experiments had already been carried out by other groups. For example, Experiment II had already been carried out by Groups C, B and E; Experiment V had been carried out by Groups D and B. Under such circumstances, several approaches were considered; for example, instructors could provide students with experimental data obtained from experiments performed in previous years and ask students to analyze the data, derive conclusions, and write reports based on what was provided by the instructors. We elected not to pursue this approach for fear of the lack of enthusiasm and understanding that could accompany data analysis without first-hand experience in attaining it. We design our experiments such that it is not obvious to students how to best collect meaningful data, and this process is part of the critical thinking aspect of the course. One unique aspect of this class is that all of the experiments are performed concurrently rather than asking the students to carry out the same experiments in series. This set of circumstances allowed us to further enhance critical thinking and retention of concepts by giving students the opportunity to not simply report their findings, but attempt to explain their experimental design, results, and mechanisms to their peers. When instruction transitioned to the online format, we held online class in a panel format for each experiment to give the students the opportunity to learn from one another in a meaningful way before being asked to investigate the particulars of the experiment with more depth on their own.

Because of time constraints, four of the six experiments (I, II, V, and VI in Figure 1) were chosen. Each section was divided into two teams for each experiment discussed during the online portion of the course — a tutorial team and a learning team (Figure 2). The *tutorial team* consisted of the students who had already written a

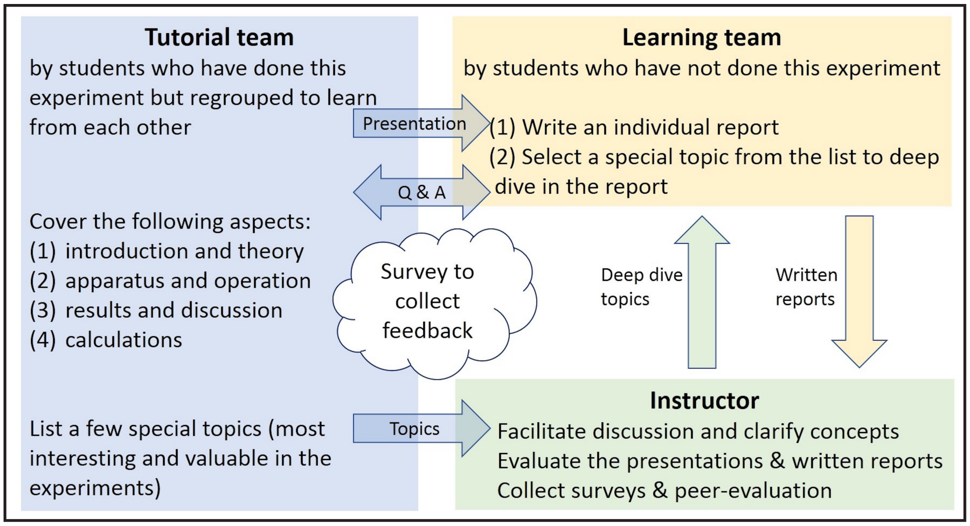

Figure 2. *The format of the online panel.*

report on the experiment, while the *learning team* comprised the groups who had not yet performed the experiment. The tutorial team was then asked to prepare a tutorial on the experiment and present it to the learning team. These two teams were shifted every week of the course depending on the experimental subject covered. This approach was in contrast to the way that the course had been taught historically, where student team membership was static for the entire semester.

The tutorial team consisted of all students (in that section) who had previously performed that experiment, either two or three groups for each experiment. This new team was then divided into four sub-groups. No more than one student (group of three) from each original group was assigned to each sub-group. The students in a sub-group were tasked with working together to prepare a tutorial on one section of the experiment — (1) introduction and theory, (2) apparatus and operation, (3) results and discussion, and (4) calculations. The tutorial teams were expected to provide specific and deep information to share their learning about the experiment. They were asked to explain the link to industrial practices, the theory and assumptions used, how they performed the experiment, how they collected and analyzed the data, and their interpretation of the results. They were also asked to address specific questions related to the experiment in more depth, as will be described later. Every sub-group prepared slides and made a presentation as a group. This environment inherently creates a unique opportunity for critical thinking that is not commonly experienced in a laboratory course. This is because, for the same experiment, different groups might have used different methods to perform and analyze the results. The members of each sub-group internally discussed the different approaches, assumptions, and interpretations. They were then asked to present a consistent message and discuss the pros and cons of the various approaches taken. This approach is potentially very beneficial for both the tutorial team students as well as the learning team students to more deeply understand the experiments and experience the nuances that accompany experimentation that can easily be missed in a virtual setting. The tutorial team members could also take this opportunity as an additional time to revisit their procedure and calculations by either correcting mistakes or gaining a more in-depth understanding. Through the discussion and debate regarding the different methodologies, students ideally arrive at a consistent message regarding the optimal solution to be presented to the learning groups. This peer-led instruction strategy has been attempted in higher education through many avenues and may help the students to solidify the knowledge and enhance their performance within this hybrid laboratory setting.[19-21]

Rather than simply aiming to minimize the negative consequences associated with a partially online laboratory experience, we aimed to take advantage of the new scenario to ideally enhance learning and critical thinking beyond what could be accomplished in a traditional laboratory course. In an effort to accomplish this, all of the groups who had performed experiments were asked to fill out surveys highlighting the most interesting and unexpected observations that they encountered, as well as listing items that they wished they had known more about given adequate time for further research. We then took this list, revised it, and added some additional topics to generate a list of special topics for students to choose from during their *deep dives* – the additional work for deeper investigation and detailed understanding beyond the original course requirements – both for the tutorial teams and the learning teams who prepared written reports. Using the "Shell and Tube Heat Exchangers" experiment as an example, students could study the following topics and report on them in more depth; typical topics included the considerations required to optimize baffle spacing in the design of a shell-and-tube heat exchanger and the effect of fluid properties (e.g. viscosity) on the performance of a heat exchanger. On the same list there were also a variety of thought-provoking questions posed that the students could research and discuss such as "What additional modifications could be made to the system to promote dropwise condensation?" and "How would the heat transfer coefficient vary at steam temperatures and pressures far beyond those employed in this experiment?" These and other open-ended topics were explored in both the oral presentations and the written reports.

Tutorial teams for any given section had either two or three members. Groups with three members presented more of these questions, providing greater engagement among all members. Providing a longer list of questions for further investigation allowed a more substantial engagement of students by giving them the opportunity to select topics to investigate that they were more interested in.

EVALUATION APPROACH FOR THE STUDENT OUTCOMES

Before they attended the panel, the students in the learning team were requested to preview the experiments utilizing the experimental materials provided by the instructors, the textbook, and other relevant research resources according to the experimental requirements. After the presentations by the tutorial groups in each section, the students participating in the learning groups asked questions and discussed their different understanding of the experiment based on the presentations. Each individual in the learning groups was then asked to write a two-page summary based on the tutorial presentation and their self-learning. This writing experience served to encourage the students to closely follow the presentation by the tutorial groups.

The approach taken provided a platform for the learning teams to leverage their peers' prior work and experience of performing the experiment in-person in hopes of gaining a broader perspective than would be obtained by simply using provided data or using a virtual experiment with limited variables. In addition, the learning group members were expected to take their peers' experiences and combine them with their own perspectives obtained by reading the provided experimental background and literature, as well as the additional literature that they obtained while addressing their deep dive topics. Our final goal was to challenge the students to think independently and build up their own knowledge about the various experimental topics.

Because each student had performed three of the possible six experiments, based on the format discussed above, the course focused on one experiment per week. This ensured that all students participated both in the tutorial group and in the learning group in the remainder of the semester. It was anticipated that this kind of role switching might help the students in developing their presentations. For example, the learning team was asked to review the tutorial presentations and list items that they felt contributed the most to their learning as well as suggested improvements. Instructors relayed this feedback, along with their own, to students in a constructive manner. We believe this could be a valuable learning experience for students on both sides.

OUTCOMES

In order to assess this course to evaluate the effectiveness of the switch from in-person to online teaching,[22, 23] evaluations are presented from both the instructors' and students' perspectives. The instructors' perspective uses the course grade distribution and the instructors' observations and comparisons with previous experience when the course was taught entirely in-person. In terms of overall scores, the students' average grade and grade distribution are comparable with previous years. Based on the instructors' experience, we believe the students' performance in terms of oral and written reports to be equal to what we have seen in prior years. Note, due to the switch of the teaching approach, the grading rubrics were adapted to reflect the altered course structure, but the expectations for students were maintained towards the depth of understanding of basic concepts as well as the ability to communicate and function as a team effectively.

The second aspect of this evaluation is the students' perspective. For that we conducted a survey at the end of the semester to solicit feedback. The list of the questions (Q1-Q22) in the survey is included in the Appendix. Additional information is available upon request from Jie Gao at jie.gao@ou.edu and Steven P. Crossley at stevencrossley@ou.edu. There were 63 students who responded to the provided survey, corresponding to a participation rate of 88%. In the online portion, since each student participated as a member of both tutorial teams and learning teams, the survey questions were divided into two parts based on the different roles. The students were asked to provide answers on a scale from 1 to 5 ranging from "Strongly Disagree" to "Strongly Agree". The survey was designed with ten questions each for the tutorial team and learning team feedback, as well as two questions regarding their overall experience.

As described above, students were asked to choose a special topic about the particular experiment they were working on to discuss in more depth. Through the survey (Q3), 84% of students considered those additional topics a valuable experience in helping them gain a deeper understanding of the unit operation in industrial application, besides just performing the experiments.

Student teams for this class had been selected by the instructor and were initially fixed for the entire semester. With the transition to the online format, teams were re-assigned weekly so that all students would have an opportunity to present with the tutorial groups as discussed in the methodology. The concern with this approach lies in our past experience that some groups require several weeks to form a good working relationship. With this new format the students were placed into a diverse working environment with rapid transitions. We feared these abrupt changes could be even more pronounced given the general anxiety and uncertainty many students were already experiencing due to the emerging shift of all their courses to the online format. Unexpectedly, most students viewed this change of group membership as a positive element of the course, and the students reported that it positively contributed to their teamwork abilities (86% positive combining "agree" and "strongly agree" for Q7). The survey shows that the communication/collaboration across different groups assisted them with a better understanding about the experimental procedure and requirements (92% for Q1), as shown in Figure 3. It also improved their ability to analyze and interpret the data (87% for Q2).

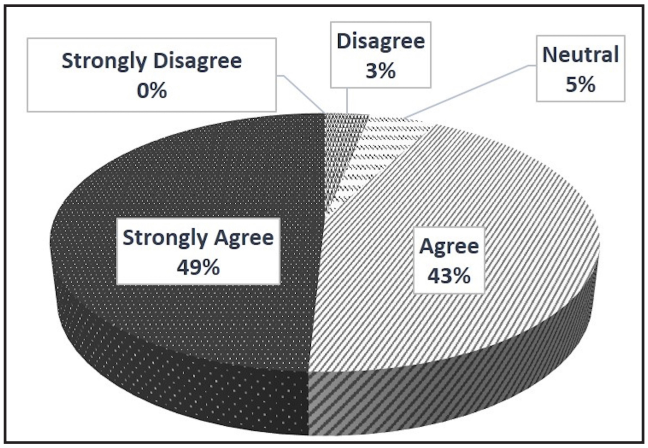

***Figure 3**. Analysis of the response to the tutorial group survey question "Giving these tutorial presentations helped me to better understand the experiments that I did already in the lab and strengthen my fundamental knowledge behind them."*

The biggest challenge for the students when moving to the online format was to write a report about an experiment that they had not actually carried out in person. Instead, they were asked to write the report after attending the presentation by the tutorial group. We find that one general challenge that junior engineering students can have is not fully recognizing their knowledge gaps and when they need to seek out additional information. This can be particularly difficult in a formal, in-class setting where raising one's hand to ask a question opens up the possibility of asking a "wrong" or "dumb" question. We tried to mitigate this hurdle by offering points to learning team students for asking a question. Extra credit was an effective incentive to encourage students to raise questions or start a discussion after the presentation. Q&A sessions were held every week following the presentation by the tutorial group. While bonus points were allocated to students for asking questions, no grade was assigned to the tutorial team regarding their response to questions, and each member of the group was allowed to respond. This was done in an effort to facilitate dialogue while minimizing anxiety of the presentations for the tutorial teams. Instructors added clarifying details as needed to help guide the students during the Q&A sessions. The students found these sessions to be both efficient and helpful for both tutorial and learning teams. 73% of students (Q5) from tutorial teams considered that the preparation for questions and the discussion in Q&A session after the presentation were valuable for them to better understand the experiments and gain the knowledge about the experiment.

The bonus point incentive did enhance participation, with more than two thirds (69% for Q16) of the students asking at least one question after the tutorial presentations. In addition, 87% of the students agreed that the tutorial presentation helped them understand the experiments and increased their fundamental knowledge of the process. 79% of the students (Q14) in the learning teams agreed that they felt better prepared to carry out these experiments than they were during their traditional preparation method. This panel format provided an interactive communication between the tutorial and learning teams, which the student survey results suggested was significantly more effective than passive listening.

Safety is an essential component emphasized in the OU ChE lab courses. We asked the tutorial team to address the safety considerations relevant to the experiment. 82.5% of the students (Q15) in the learning teams valued this part of the presentation and, though they didn't do these experiments in person, noted that they were aware of the safety concerns and issues in the experiments through the tutorial presentation by their peers and their individual two-page report writing. This was also consistent with the instructors' impression.

Oral presentations by the students for both the in-person (before the campus was closed) and online portion of the class were recorded so that the students could review them. For the in-person portion, the students had an audience (four other students and the instructor were present during the presentation), and each student was required to view their own video and write a self-critique of their presentation. Previously, students had found this exercise to be awkward, but ultimately helpful for improving their oral presentation skills. For the online portion we also video recorded the tutorial team presentations, but we did not ask the presenters to critique their own presentations. Based on the survey (Q17), 84% of the learning team watching the presentation reviewed the video before writing their two-page report. On the other hand, the tutorial team members were less motivated to review their video after the presentation, and only 35% of the presenters (Q6) reported reviewing their own presentation. This observation demonstrates that our previous method of requiring the students to write a self-critique is a valuable approach and one that should be reconsidered in future iterations. On the other hand, a majority of the students (71% for Q9) in tutorial teams valued the feedback from the instructor and the audience, and considered this feedback helpful for them to improve communication skills for oral presentation.

In addition to these positive outcomes, we also note several areas where the switch to an online venue negatively impacted student learning. First, only a bit more than half of the students (57%) agreed that the group work through virtual interaction among sub-group members was as effective and smooth as was in-person group work before the switch. This was quite understandable, since almost no one had prior experience with online group work before the Spring 2020 semester while nearly all of the students had participated in some form of in-person group work prior to this semester. Based on the responses above, it appears that the dissatisfaction with virtual group work was not due to the shifting makeup of teams (see our discussion above about students' response to subgroup setting), but more due to the online venue. Future iterations will likely lead to improved responses as students gain more experience with virtual meetings.

Even with these efforts to improve the overall outcome, online teaching cannot completely replace the in-person hands-on experience of a laboratory course. This is reflected by Figure 4 (Q21), showing that only 22% of the students agreed the switch to online didn't affect their lab course experience. When students were asked about the options for limited access to the lab class in the Fall 2020 semester, a large portion of them (76% for Q22) would prefer to be back to in-person lab, if possible, in a safe manner rather than to continue operating some type of online format for lab class. As educators, we also believe strongly in the value of a hands-on experience if it can be done safely. The hands-on experience is essential for our ChE students, although they have shown that they can do some work online. Their in-person experience interacting directly with the equipment allows them the opportunity to face and solve unplanned problems. This essential part of the lab class that develops their confidence to deal with the unknown does not seem to be reproduced as well with this online lab format. While the approach used here — incorporation of deeper dives into the subject matter, and expanded discussion of the details of the experiment as well as trials involved — provides an advantage over simply analyzing data without these discussions, online discussions do not fully replace the in-person laboratory experience.

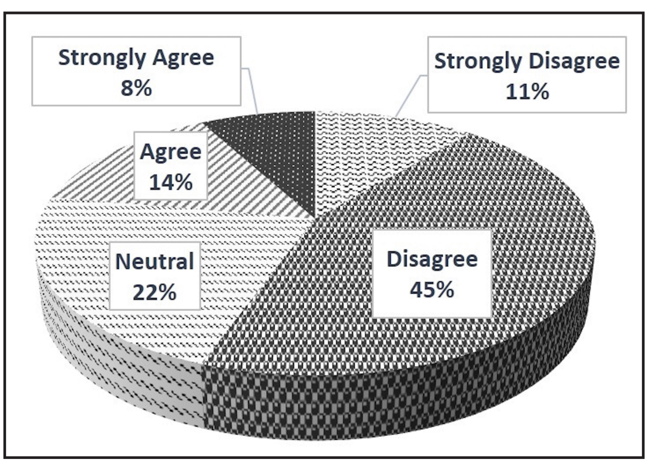

Figure 4. *Analysis of the response to the survey question "The online portion doesn't affect my overall experience of this lab class" to both the tutoring and learning groups.*

The survey also provides a qualitative assessment for the online teaching of this lab course. Overall, based on the generally positive feedback from students, it seems our online strategy for Unit Ops Lab teaching was a very good attempt to move from in-person to virtual learning during this unique period. Our success was based on the partial in-person operations in the lab before switching to the online format. Through the three experimental periods of in-person lab teaching, the students had obtained the training and some hands-on experience to design and operate the ChE unit operations in group work. This provided the students with intuition about the specific chemical engineering equipment and unit operations. Then the following online portion further enhanced their understanding of the principles and analysis methodologies in the remaining experiments of the semester. They could continue practicing the communication skills and teamwork that they had already begun to develop.

Prior to online learning, this class was designed to effectively assess student skills, both for the course objectives as well as ABET Student Outcomes 3, 5, and 6. The strategy described here is likely more suitable for a hybrid teaching mode (part in-person, part online) rather than a fully online lab class. The hybrid teaching model could also be a good option for the situation of limited lab resources.[23] On the other hand, we are very satisfied with the participation of the students; amid this pandemic, students were dedicated to the course as evidenced by attendance rate higher than 96%. From the students' perspective, the course evaluation, which is conducted by the university and focused on evaluation of the instructor, is comparable with previous years. In other words, moving online does not affect students' evaluation of instructors; this agrees with our impression when interacting with students.

While we have noted that there are distinct advantages to hands-on learning experiences, students did view the tutorial addition quite positively, both from the perspective of those who carried out the tutorial as well as those who participated in learning teams. Figure 5 highlights the student responses to the question (Q1 vs. Q11) asking if the tutorials "helped me to understand the experiments and strengthen my fundamental knowledge behind them." For the tutorial team this involved the efforts that they put into preparing these presentations, while for the learning team it involved viewing the presentations and interacting via the Q&A sessions afterward. Overall, the team giving the tutorial presented a slightly more favorable response; this agrees with what we discussed above about the advantage of the peer-led instruction strategy.[19-21] The general outcome from both groups was

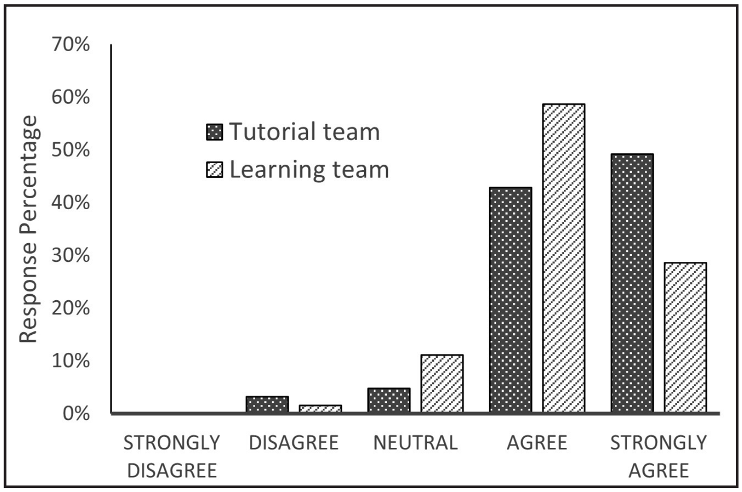

Figure 5. *Student responses to the question that the tutorial presentations "helped me to understand the experiments and strengthen my fundamental knowledge behind them" from those participating in the learning teams and the tutorial teams.*

overwhelmingly positive, and thus this approach should be considered to further boost learning outcomes in future years even when a virtual venue is not required.

PROSPECTIVE FUTURE DEVELOPMENT

Our experience with the abrupt switch to fully online teaching for the ChE lab course has suggested several valuable lessons to better prepare for future uncertainties. First, the addition of more videos of experiment operations by the instructors is recommended to facilitate learning. Further, we have not explored in this manuscript other benefits that may arise by asking students on the learning team to analyze and interpret data in more depth. While we do not feel this is an adequate approach alone, when accompanied with these deep dive discussions and tutorials, it may further advance the learning experience. Those videos could be supplemented with oral presentations by the students, thus allowing the students to have a better chance to visualize the experiments as well as to get the perspective of a student user. Alternatively, the groups can be asked to prepare a video presentation of operating the experiment and/or piece together a visual manual for the experiments, through which their communication skills can also be improved.

There are certainly other possibilities for teaching the lab classes fully online that we have not explored this semester. These might become useful should another extreme circumstance like this pandemic arise, but it might also help to provide a chance for students who cannot attend in-person lab courses in the way that they have been traditionally taught.[24-26] For example, with virtual reality (VR) programs, the students may operate a virtual facility to increase operation experience.[27] Alternate forms of group work, by integrating the coordination and communication of in-person and remote team members, would be a valuable direction to explore as well. For example, during conditions where contact is limited, a portion of students may operate remotely while still maintaining their degree of learning. It might be valuable to provide a friendly, interactive interface between the equipment and the students' computer through which they can control the system remotely in order to improve the students' experience.

The important outcome presented here is that, during limited exposure to hands-on activities, the knowledge gained in the lab course can be maximized by asking students to explore topics in more depth and present them to their peers. This not only benefits the experience of those who cannot attend in person but has a potentially even greater impact on the presenting students themselves.

Online lab courses benefit not only the students affected by the pandemic but also those students in remote areas or in developing countries who want to participate in a ChE lab course, if critical hardware and software for distant learning could be implemented.[28-32] While online teaching of a lab course may pose a great challenge, it also offers great opportunities.

REFERENCES

1. Moorhouse BL (2020) Adaptations to a face-to-face initial teacher education course 'forced'online due to the COVID-19 pandemic. *Journal of Education for Teaching*. 1-3. https://doi.org/10.1080/02607476.2020.1755205
2. Telles-Langdon DM (2020) Transitioning University Courses Online in Response to COVID-19. *Journal of Teaching and Learning*. 14(1):108–119. https://doi.org/10.22329/jtl.v14i1.6262
3. Terenko O and Ogienko O (2020) How to Teach Pedagogy Courses Online at University in COVID-19 Pandemic: Search for Answers. R*omanian Journal for Multidimensional Education/Revista Romaneasca pentru Educatie Multidimensionala*. 12(1Sup2): 173-179. https://doi.org/10.18662/rrem/12.1sup2/261
4. Sandhu P and de Wolf M (2020) The impact of COVID-19 on the undergraduate medical curriculum. *Medical Education Online*. 25(1):1764740. https://doi.org/10.1080/10872981.2020.1764740
5. Gray AC, Steel A, and Adams J (2020) Attitudes to and Uptake of Learning Technologies in Complementary Medicine Education: Results of an International Faculty Survey. *The Journal of Alternative and Complementary Medicine*. 26(4):335-345. *https://doi.org/10.1089/acm.2019.0319*
6. Yueh H-P, Liang C, and Liu Y-L (2018) Influences of learning competency and e-learning implementation on learning outcomes of engineering students. *The International Journal of Engineering Education*. 34(4):1376-1383.
7. Worley WL and Tesdell LS (2009) Instructor time and effort in online and face-to-face teaching: Lessons learned. *IEEE Transactions on Professional Communication*. 52(2):138-151. https://doi.org/10.1109/TPC.2009.2017990
8. Weisman D (2010) Incorporating a collaborative web-based virtual laboratory in an undergraduate bioinformatics course. *Biochemistry and Molecular Biology Education*. 38(1):4-9. https://doi.org/10.1002/bmb.20368

9. Elliott W, Choi E, and Friedline T (2013) Online statistics labs in MSW research methods courses: Reducing reluctance toward statistics. *Journal of Social Work Education*. 49(1):81-95. https://doi.org/10.1080/10437797.2013.755095
10. Borrero AMM and Márquez JMA (2013) Interaction of real robots with virtual scenarios through augmented reality: Application to robotics teaching/learning by means of remote labs. *The International Journal of Engineering Education*. 29(3):788-798.
11. Duan B, Ling K-V, Mir H, Hosseini M, and Gay RKL (2005) An online laboratory framework for control engineering courses. *International Journal of Engineering Education*. 21(6):1068-1075.
12. Borrero AM and Márquez JMA (2012) A pilot study of the effectiveness of augmented reality to enhance the use of remote labs in electrical engineering education. *Journal of Science Education and Technology*. 21(5):540-557. https://doi.org/10.1007/s10956-011-9345-9
13. Kilani M, Torabi K, and Mao G (2018) Application of virtual laboratories and molecular simulations in teaching nanoengineering to undergraduate students. *Computer Applications in Engineering Education*. 26(5):1527-1538. https://doi.org/10.1002/cae.21940
14. Kuchirka Y, Petriv M, Baran S, Ursutiu D, and Samoila C (2016) Online Teaching and Laboratory Course on Measurement Methods. *International Journal of Online Engineering*. 12(3):4-7. http://dx.doi.org/10.3991/ijoe.v12i03.5233
15. ABET. Criteria for Accrediting Engineering Programs, 2019 – 2020. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/ accessed June 12, 2020
16. Purkayastha S, Surapaneni AK, Maity P, Rajapuri AS, and Gichoya JW (2019) Critical Components of Formative Assessment in Process-Oriented Guided Inquiry Learning for Online Labs. *Electron J E-Learn*. 17(2):79-92. 10.34190/Jel.17.2.02.
17. Dietrich N, Kentheswaran K, Ahmadi A, Teychene J, Bessiere Y, Alfenore S, Laborie S, Bastoul D, Loubiere K, Guigui C, Sperandio M, Barna L, Paul E, Cabassud C, Line A, and Hebrard G (2020) Attempts, Successes, and Failures of Distance Learning in the Time of COVID-19. *Journal of Chemical Education*. 97(9):2448-2457. https://doi.org/10.1021/acs.jchemed.0c00717
18. Dukes AD (2020) Teaching an Instrumental Analysis Laboratory Course without Instruments During the COVID-19 Pandemic. *Journal of Chemical Education*. 97(9):2967-2970. https://doi.org/10.1021/acs.jchemed.0c00648
19. Schneider LN and Meirovich A (2020) Student Guided Learning-from Teaching to E-learning. *Romanian Journal for Multidimensional Education/Revista Romaneasca pentru Educatie Multidimensionala*. 12(1Sup2):115-121. https://doi.org/10.18662/rrem/12.1sup2/254
20. Amaral KE and Vala M (2009) What teaching teaches: Mentoring and the performance gains of mentors. *Journal of Chemical Education*. 86(5):630-633. https://doi.org/10.1021/ed086p630
21. Roberts V, Malone K, Moore P, Russell-Webster T, and Caulfield R (2020) Peer teaching medical students during a pandemic. *Medical Education Online*. 25(1):1772014. https://doi.org/10.1080/10872981.2020.1772014
22. Zhou H, Lei Z, Hu W, Deng Q, Zhou D, and Liu Z-W (2017) A multi-criteria method for improving the assessment of students' laboratory work using online laboratory. *Int. J. Eng. Edu*. 33(5):1654-1663.
23. Ardissone AN, Oli MW, Rice KC, Galindo S, Urrets-Zavalia M, Wysocki AF, Triplett EW, and Drew JC (2019) Successful Integration of Face-to-Face Bootcamp Lab Courses in a Hybrid Online STEM Program. *Journal of Microbiology & Biology Education*. 20(3). https://doi.org/10.1128/jmbe.v20i3.1769
24. May D (2020) Cross Reality Spaces in Engineering Education–Online Laboratories for Supporting International Student Collaboration in Merging Realities. *International Journal of Online and Biomedical Engineering (iJOE)*. 16(03):4-26. https://doi.org/10.3991/ijoe.v16i03.12849%0d
25. Guo J, Kettler D, and Al-Dahhan M (2007) A chemical engineering laboratory over distributed control and measurement systems. *Computer Applications in Engineering Education*. 15(2):174-184. https://doi.org/10.1002/cae.20108
26. Diwakar S, Kumar D, Radhamani R, Sasidharakurup H, Nizar N, Achuthan K, Nedungadi P, Raman R, and Nair B (2016) Complementing education via virtual labs: Implementation and deployment of remote laboratories and usage analysis in south indian villages. *International Journal of Online and Biomedical Engineering (iJOE)*. 12(03):8-15. http://dx.doi.org/10.3991/ijoe.v12i03.5391
27. Radianti J, Majchrzak TA, Fromm J, and Wohlgenannt I (2020) A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*. 147:103778. *https://doi.org/10.1016/j.compedu.2019.103778*
28. Theyßen H, Struzyna S, Mylott E, and Widenhorn R (2016) Online physics lab exercises—A binational study on the transfer of teaching resources. *International Journal of Science and Mathematics Education*. 14(5):865-883. https://doi.org/10.1007/s10763-014-9613-2
29. Harward VJ, Del Alamo JA, Lerman SR, Bailey PH, Carpenter J, DeLong K, Felknor C, Hardison J, Harrison B, and Jabbour I (2008) The ilab shared architecture: A web services infrastructure to build communities of internet accessible laboratories. *Proceedings of the IEEE*. 96(6):931-950. https://doi.org/10.1109/JPROC.2008.921607
30. Ayodele KP, Inyang IA, and Kehinde LO (2015) An iLab for teaching advanced logic concepts with hardware descriptive languages. *IEEE Transactions on Education*. 58(4):262-268. https://doi.org/10.1109/TE.2015.2395996
31. Wu M, She J-H, Zeng G-X, and Ohyama Y (2008) Internet-based teaching and experiment system for control engineering course. *IEEE Transactions on Industrial Electronics*. 55(6):2386-2396. https://doi.org/10.1109/TIE.2008.921229
32. Henke K, Vietzke T, Wuttke H-D, and Ostendorff S (2016) GOLDi–Grid of Online Lab Devices Ilmenau. *International Journal of Online and Biomedical Engineering (iJOE)*. 12(04):11-13. http://dx.doi.org/10.3991/ijoe.v12i04.5005 ❐

APPENDIX

Supporting Information

	Online Class Survey Questions from the survey given at the end of the semester to solicit feedback. 63 students responded to the provided survey, corresponding to a participation rate of 88%; 1 of the students did not provide feedback on questions 16 and 17. Questions 1-10 and 11-20 are answered based on the tutorial experience and the learning experience, respectively; questions 21-22 are answered based on the overall experience.					
	Question	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
1	Giving these tutorial presentations helped me to better understand the experiments that I did already in the lab and strengthen my fundamental knowledge behind them.	0.0%	3.17%	4.76%	42.86%	49.21%
2	The process of preparing my presentation improved my ability to analyze and interpret data.	0.0%	0.0%	12.7%	47.62%	39.68%
3	The additional topics helped me gain a bigger picture of the Unit Operations in industrial application besides performing the experiments.	0.0%	1.59%	14.29%	39.68%	44.44%
4	After communicating with other groups in preparation for my presentation, I have a better understanding about the experimental procedure and required items.	0.0%	0.0%	9.52%	49.21%	41.27%
5	The questions in the Q&A session after my presentation are valuable for me to better understand the experiments and the knowledge.	1.59%	7.94%	17.46%	42.86%	30.16%
6	I watched the video of my presentation later.	17.46%	23.81%	23.81%	14.29%	20.63%
7	Subgroup settings provided me an opportunity to work with different people and benefitted my teamwork abilities.	0.0%	0.0%	14.29%	31.75%	53.97%
8	The group work (to make plans, collaborate on the presentation preparation) between me and the sub-group members is as effective and smooth as in person before.	0.0%	22.22%	20.63%	36.51%	20.63%
9	The presentation feedback and questions helped me improve my communication skills in my oral presentation.	0.0%	4.76%	23.81%	36.51%	34.92%
10	I enjoyed the process to give online presentations to my classmates.	1.59%	1.59%	25.40%	47.62%	23.81%
11	The presentation given by others helped me understand the experiments and the fundamental knowledge behind.	0.0%	1.59%	11.11%	58.73%	28.57%
12	The presentation given by others helped me analyze and interpret data.	0.0%	7.94%	25.40%	46.03%	20.63
13	The report writing helped me understand the overall knowledge about the experiments.	0.0%	1.59%	12.70%	42.86%	42.86%
14	After the presentation, I think I am better prepared and, if I am asked to do the experiments, I can do better than the normal way that we prepared for the lab experiments before moving online.	1.59%	3.17%	15.87%	34.92%	44.44%
15	I believe I am fully aware of the safety concerns and issues in these experiments though I didn't do these experiments in person.	1.59%	4.76%	11.11%	50.79%	31.75%
16	I asked a question in the Q&A session.	19.05%	11.11%	3.17%	15.87%	49.21%
17	I watched the video/slides of the presentation again to prepare my report.	1.59%	6.35%	6.35%	17.46%	66.67%
18	The report writing helped my writing skills as much as the previous way as in person class.	1.59%	7.94%	25.40%	36.51%	28.57%
19	Not conducting two experiments and hands-on operating the units in person is a big loss to my experience of this lab class.	1.59%	6.35%	30.16%	33.33%	28.57%
20	I more favor to be on the side of the learning team.	6.35%	30.16%	44.44%	7.94%	11.11%
21	The online portion doesn't affect my overall experience of this lab class.	11.11%	44.44%	22.22%	14.29%	7.94%

Question 22: If the lab still has limited access in Fall semester, please choose one from below:

(A) I would prefer to be back to lab if possible in a safe manner (e.g. following social distancing….). (76.19%)

(B) I would prefer to continue operating online for lab class. (11.11%)

(C) I don't have strong preference. (12.70%)