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Comparing labs before, during, and after COVID in a Measurements and Analysis Course

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Comparing labs before, during, and after COVID in a Measurements and Analysis Course

Traditional lab courses were a source of stress for instructors during the COVID pandemic. Switching over to online or hybrid models of instruction, while not a huge difficulty for lecture classes, proves to be an enormous challenge for lab classes. In the Mechanical Engineering department at Northeastern University, the required junior level lab course in Measurements and Analysis was extensively reworked to maintain a highly hands on and open-ended lab experience. Starting in Fall 2020, the lab experiments were modified to use Arduino based sensors that allowed for experimentation either on campus or at home. The Arduino kits were the same for on- and off-campus students, and all lab groups contained students from both cohorts. Students shared data from on-campus and off-campus experiments to complete the lab reports. These hybrid labs were in place for Fall 2020 and Spring 2021. In Fall 2021 students returned to campus full time. Rather than reverting to the previous on campus labs, the Arduino based experiments were modified slightly for students working completely in the lab. Student reactions to the labs before, during, and after the COVID interruption were assessed using student surveys. These surveys probed whether students found the labs engaging, whether the labs helped them learn course materials, whether the labs were frustrating or confusing, and whether the lectures/lab handouts were clear and helpful. Data from previous studies was combined with data from the three most recent terms to gauge the effectiveness of the new lab experiments.

Experiments during the initial hybrid lab term were rated as more confusing than previous terms. This was resolved and improved upon in subsequent terms. Despite the initial frustration with the hybrid labs, they were generally rated more interesting and engaging than the pre-COVID labs. Students also found that the new labs, both on and off campus, helped them learn the course concepts better than the pre-COVID labs. No correlations were found between any of the survey items and lab report grades. Only Fall 2020 showed any significant correlations between any of the survey items and whether the students were on or off campus when they performed the lab. However, there was a significant difference (P=0.0004) between the initial hybrid lab term and the subsequent terms when it came to equally engaging all students in the lab group. This can perhaps be attributed to the combination of improved lab handouts and, paradoxically, having less equipment set up for the students prior to lab. Overall, the new labs which built on skills learned earlier in the curriculum proved to be more successful at helping the students feel engaged while mastering the material. Additionally, lessons learned during the introduction of the new labs will be discussed.

Introduction

This work is a continuation of a work in progress paper submitted to the 2021 ASEE conference [1]. The original paper discussed the details of the redesign of a measurements and analysis lab course in order to allow for at home experimentation for students who were not able to be on campus due to the COVID pandemic. This lab was run in a hybrid format where every lab team had both online and on campus students. Kits were sent to all students to allow them to perform their part of the experiment at home if necessary. Lab analysis questions could only be answered by combining at home and on campus data to promote positive interdependency between students. The course in question had been extensively redesigned to be more open-ended in the past [2] and the goal was to be able to maintain this open-ended and hands-on character despite the need for COVID related distancing.

The need for hands on experimentation in engineering laboratories has been well established. Feisal and Rosa determined that hands on laboratory activities are necessary in order to teach students skills such as choosing sensors, comparing theoretical and experimental results, and practicing experimental design among other skills [3]. Kolb's experiential learning cycle has two stages which require hands on activity, namely, the concrete experience stage and the active experimentation stage [4]. Abdulwahed and Nagy [5] applied Kolb's theory specifically to engineering laboratory education. They claimed that virtual and remote experimentation could act as concrete experiences, as well as abstract conceptualization and active experimentation. This would seem to indicate that virtual, simulated, or remote laboratory experiments are equally as valuable in teaching hands-on skills as traditional physical laboratories. Shekoyan et.al. found that videos could act as concrete experience as in Kolb's framework. They conceded that it was imperative to study the literature on pedagogy and adjust assessments prior to the online course and design the course purposefully around the virtual experiences [6]. However, other research has shown that virtual experiences are often not as effective as in person experiences in conveying lab related material [7]. While for some disciplines, such as electrical and computer engineering, the differences between virtual and actual experiments are small [8], for other disciplines such as chemical engineering there are some topics that are very difficult to simulate effectively.

Benefits to virtual laboratories include fewer necessary physical resources, the ability for asynchronous experimentation, and the ability in some cases to provide more intellectually challenging problems than traditional theory-based labs [9]. However, these courses come with their own set of problems. Disparities in resources such as Internet access and reliable computer hardware can lead to problems with inequity between students [10]. This problem may be particularly noticeable in historically underserved populations. Some universities attempted to solve this problem by allowing students to remotely log into expensive software programs using the university VPN. However, this often led to overload of the VPN and did not solve the problem of individual students not having high quality Internet at home [11]. Some authors, while reporting successful achievement of student learning goals, saw that there were increased difficulties with teamwork and communication between students in the virtual mode [9]. Additionally, some researchers reported a decrease in the amount of student learning, even though they gained some self-efficacy skills from the experience [12].

Like the author, many educators attempted some sort of hybrid lab model in response to the demands of the COVID pandemic. Recently published literature shows a variety of outcomes for these newly developed lab courses. Several authors reported moving completely to online simulations and videos in order to convey the material that could no longer be experienced in the physical lab. These courses included mechatronics courses, dynamics and control courses, and fluid mechanics courses [13-15]. Although some authors found this to be an excellent way to improve upon outdated physical labs [15], others reported that the students were unenthusiastic about the simulated experiments [14]. Learning outcomes did not seem to suffer from the move to virtual labs but student engagement was either not discussed or was reported as tepid at best. Mirza reported a hybrid instruction method where there was a combination of virtual face to face meetings, asynchronous lectures, and live video during synchronous lab sections [16]. One student from each lab group was physically present in lab while the others were tuning in live but remotely. The students watching the lab virtually were reported to be disengaged and not participating in the activity. Although this allowed students to experience physical experimentation in turns, it did not seem to promote complete engagement. Other researchers found that the shift to virtual labs caused students to question the quality of their education [17].

Several authors also attempted to use kits that were mailed to the students as a way of providing hands on experiments. In some cases, these were combined with virtual labs. Liang et. al. used a combination of equipment mailed to the students for home experiments, remote control, and virtual simulation [18]. Student surveys revealed that the students preferred the at home experiments to any of the virtual activities. Another paper describes comparing 4 lab courses which were converted to a remote format [19]. Some activities included experiments using kits mailed to the students which were returned at the end of the course. Remote hardware and software labs which accompanied the at home experiments had several software and hardware problems. There were also issues with teamwork due to time zone differences and differences in Internet quality between students. The authors reported that most students complained about the remote labs. They conceded that remote labs are viable but require practice in both teaching and administrating these types of classes. This was confirmed by other authors who found that remote learning relied heavily on instructor ability to effectively harness available technology to convey concepts remotely [20]. Instructors who were unfamiliar with active learning strategies and unaccustomed to using online tools were found to struggle with rapidly converting to a virtual format. In contrast, instructors who were already proficient in active learning and fully used available course management tools had much less of a learning curve.

In summary, the research seems to indicate that hands-on activities, while difficult to create during remote classes, are still highly valued by the students. Virtual and remote learning seems to work reasonably well for subjects that are already highly computer dependent such as mechatronics and electrical engineering concepts. Courses which rely on measuring physical quantities or interacting with non-electronic equipment seem to have mixed success in going completely virtual. Success in these courses relies heavily on instructor knowledge of virtual pedagogy and time for planning and developing online tools. Teamwork among students also needs to be carefully managed to allow for complete engagement of all students. Virtual activities also require sensitivity to disparities among students in terms of computer resources and Internet access. The current work hopes to show that not only is it possible to create and administer hybrid or remote labs involving physical experiments successfully, but it is also possible to use the lessons learned when returning to completely on campus lab courses.

Course details and COVID related adjustments

The lab course which is the focus of this paper is entitled Measurements and Analysis with Thermal Science Application. It is a required junior level lab course in the Mechanical Engineering department at Northeastern University. The goal of this course is to teach students the principles of design of experiments (DOE) and introduce them to sensors, data acquisition, and data analysis. Additional details about the course can be found in [1]. Although this course contains a term project, in class active learning problems, and pre-lab homework this study focuses primarily on the lab experiments.

Prior to COVID there were six lab experiments in the course. Table 1 shows the titles for the pre-COVID labs as well as the main concepts taught during the labs. All labs were performed in teams of three to four students in a traditional laboratory space. The labs were designed to be more and more open-ended as the term progressed to allow students to build their confidence in executing and designing open-ended experiments. As previous lab courses tended to be theory based and limited in outcomes, this was a mental hurdle for some students. A feature of the pre-COVID labs was a course goal to teach students the LabView data acquisition software. This was used in conjunction with the Vernier SensorDAQ hardware and Vernier sensors along with additional analog sensors. Although time was devoted to teaching the LabView software in both lecture and lab sessions, the students were expected to learn much of the information through online tutorials provided by the manufacturer. This set of experiments had been in place for several years prior to the COVID interruption. During Spring 2020, the campus was shut down soon after Lab 4 had occurred. As Labs 5 and 6 required on campus equipment that was not easily made virtual on short notice, these two labs were scrapped for that term.

Table 1: Lab titles and topics for Pre-COVID labs, Fall 2019-Spring 2020. Note that labs 5 and 6 were not performed in Spring 2020 due to a campus shutdown.

Lab number	**Lab title**	**Concepts taught**	**Sensors and Data Acquisition Used**
Lab 1	Pressure and Calibration	Pressure measurement, Calibration, Accuracy and Precision	Deadweight tester, Pressure gauges and transducers, SensorDAQ with LabView
Lab 2	Temperature Measurement	Temperature measurement, Calibration, Measuring time constants, Accuracy and Precision	Thermometers, Thermocouples, RTD’s, Thermistors, Fixed temperature baths, SensorDAQ with LabView
Lab 3	Strain Measurement	Strain gauges, Wheatstone bridge circuits, Calibration, Accuracy and Precision	Strain gauge indicator box, Pre-applied strain gauges, Calibration weights
Lab 4	Heat Transfer in Crossflow	Heat transfer measurements, Determining heat transfer coefficients, Comparing experimental and theoretical results	Thermocouples, SensorDAQ with LabView, Indicating power supplies, Multimeters
Lab 5	Mechanical Power	Design of experiments, Measuring electrical and mechanical power, Power curves	Generators, SensorDAQ with LabView, Voltage probes, Hall effect sensors, Load cells, Contact tachometers
Lab 6	Wind Tunnel Testing	Air flow measurements, Design of Experiments, Comparing experimental and theoretical results, Electrical signals	Pitot tubes, Pressure transducers, Oscilloscopes, Anemometers, Multimeters, Non-contact tachometers, SensorDAQ with LabView

During the summer of 2020 it became known that the campus was going to be in a hybrid mode for the Fall 2020 semester. The plan was for a greatly reduced number of students who were physically on campus at any time. For some students this would mean attending lectures partly in person and partly via synchronous video. Some students elected to return home because of the partial shutdown and thus would attend lectures either synchronously or asynchronously depending on their time zone. The lab portion of the course similarly had a mix of students who would be physically present and those who would be remote. Given these parameters, the lab course was completely redesigned to allow all students to do as much physical experimentation as possible. One particularly important point was requiring all students to be in lab groups that contained both on campus and off campus students. This promoted engagement by all students and allowed the remote students to feel equally connected to the course.

As a starting point for the new experiments the decision was made to switch from LabView and SensorDAQ to Arduino based sensors. The Arduino platform consists of open source hardware and software that supports a wide range of sensors. Students are required to buy a kit of Arduino equipment for their first year engineering program. Thus, students in the measurements class could be expected to have familiarity with Arduino hardware and coding and a kit of basic pieces of Arduino hardware to start with. In addition to these reasons for switching to Arduino, there were some problems with the LabView software even prior to COVID. In order to use the SensorDAQ it was necessary to run a local copy of the LabView program on an individual student's laptop. At the time, LabView only worked on PC laptops which left Macintosh users unable to work on the programs easily outside of class. The program was available over the university VPN but again one could only program and not run sensors, as the sensors required a local install of the Vernier SensorDAQ software. This difficulty coupled with the large learning curve for LabView had been the source of many student complaints in previous terms. Arduinos were already familiar, small, and low cost and it was easy to send additional Arduino parts to students to supplement the existing kits. For details about the contents of the lab kits see [1].

Table 2 shows the titles and topics for the redesigned lab course. This version of the course has been in place from Fall 2020 to the present. Most of the concepts taught were unchanged, however they were taught in different order or emphasized in different experiments. All the experiments used Arduino data acquisition and sensors with the circuit diagrams and codes provided on the course management system. This was done as students had not generally practiced much with Arduino between first year and junior year. Students were encouraged to alter the code as needed to achieve their particular purpose. The dynamic temperature lab, Lab 3 in Table 2, and the wind tunnel lab, Lab 6 in Table 2, were essentially unchanged from previous terms. Lab 1 moved the concept of calibration from a pressure transducer to the ultrasonic sensor already included in the first year Arduino kit. Lab 2 was a new experiment designed to step the students through the process of designing an experiment to create power curves for a solar cell. This was in response to a need for additional instruction in design of experiments as observed by the instructor. The original strain experiment (Lab 4) had required a piece of aluminum with prewired strain gauges and a strain gauge indicator box, which were impossible to send to off campus students. The new Lab 4 focused on using a load cell to acquire data points for statistical data analysis. Lab 5 replaced the previous heat transfer experiment involving a heated cylinder in crossflow with a lab based on the first law of thermodynamics. Students at home studied an open thermodynamic system in the form of a light bulb in a holder, while students on campus studied a closed thermodynamic system in the form of a light bulb in a holder contained in an insulated box. The goal for all labs was to allow students to perform essentially the same experiment regardless of their location.

Table 2:Lab titles and topics for During and Post-COVID labs, Fall 2020-Fall 2021

Lab number	**Lab title**	**Concepts taught**	**Sensors and Data Acquisition**
Lab 1	Calibrating Ultrasonic Sensors	Calibration, Accuracy and precision, Distance measurement	Arduino ultrasonic module, Gauge blocks, laser distance gauges
Lab 2	Designing a Solar Power Experiment	Design of experiments, solar power, Lux sensors, Voltage and power measurement	Arduino lux sensors and voltage measurement, solar cells
Lab 3	Dynamic Temperature Signals	Temperature measurement, Calibration, Measuring time constants, Accuracy and Precision	Arduino thermocouple and RTD modules, Fixed temperature baths, Arduino transistor temperature sensors
Lab 4	Load Cells and Data Analysis	Calibration, Load cells, Statistical data analysis, Uncertainty analysis	Arduino load cell, Calibration weights
Lab 5	1st Law of Thermodynamics	Heat transfer measurements, Determining heat transfer coefficients, Predicting results from theory, Dynamic temperature measurements, Design of Experiments	Arduino thermocouple modules, Arduino lux sensors
Lab 6	Wind Tunnel Testing	Air flow measurements, Design of Experiments, Comparing experimental and theoretical results, Electrical signals, Wind turbines	Pitot tubes, Pressure transducers, Oscilloscopes, Arduino voltage measurement, Anemometers, Multimeters, Non-contact tachometers

During the Fall 2021 semester Northeastern University returned to primarily on-campus instruction. This meant that there would no longer be a cohort doing experiments off campus.

The labs developed for the hybrid mode of instruction were retained for the return to normal operations. Some adjustments were made to the instructions to accommodate the complete lab group being in one location. Instead of lab kits being provided to each individual student, one kit was given to each lab group to be shared among the group members. Although the intent was for all students to be on campus there were a handful of students who had permission from the college to continue remote learning. The new labs allowed for kits to be sent to those students with only minor adjustments to instructions to allow them to work with their lab group.

Methodology and Research Questions

As discussed in [1], student surveys were used to determine student perception of the value of the various lab experiments. These surveys have been administered every term since Spring 2011 as a way of tracking the effect of changes in the course [21]. Over time, the questions have changed slightly as shown in Table 3. In all cases these questions were asked regarding each individual lab experiment. These surveys included both Likert scale and open response questions. Prior to COVID the questions asked students to rate how well the experiment helped them learn course concepts, whether or not it was interesting and engaging, whether or not it was frustrating and confusing, whether they felt the class was supported by lecture, and whether they thought these skills learned could be transferred to other problems. At the time the author was also working with a committee to improve lab experiences for the students throughout the department, thus the open-ended questions focused on new topics for the measurements course as well as information about how the entire departmental lab program could be improved. During Fall 2020 when the new hybrid labs were introduced, similar questions were asked about student engagement, how well the lab reinforced course concepts, whether the lab instructions were clear, and whether the lab was frustrating or confusing. Open response questions were rewritten to focus on online activities as these activities were new and could benefit from student feedback. Questions about the valuable and challenging aspects of the experiments were designed to give more granular information about specific lab activities in the measurements course. During Spring 2021 the same survey questions were used with the addition of a question on whether the lab was supported by lecture. In Fall 2021 the Likert scale questions remained the same as Spring 2021, however the open response questions discussing online experiences were removed to focus solely on challenging and valuable aspects of the individual experiments.

Table 3: Comparison of survey questions over time

Fall 2019-Spring 2020 Questions	**Fall 2020 Questions**	**Spring 2021 Questions**	**Fall 2021 Questions**
Likert Scale Questions (5 = Strongly Agree, 1 = Strongly Disagree)			
This lab helped me learn the material	Lab x engaged all group members.	Lab x engaged all group members.	Lab x engaged all group members.
This lab was interesting and engaging	Lab x helped me learn course concepts.	Lab x helped me learn course concepts.	Lab x helped me learn course concepts.
This lab was frustrating and confusing	The instructions for Lab x were clear.	The instructions for Lab x were clear.	The instructions for Lab x were clear.
This lab was supported by lecture	Lab x was frustrating and/or confusing.	Lab x was frustrating and/or confusing.	Lab x was frustrating and/or confusing.
I can imagine applying some of this information to other problems		Lab x was supported by lecture	Lab x was supported by lecture
Open-ended Questions			
Can you think of any topics/experiments that you would like to see added to Measurements and Analysis?	Compare this lab experiment to other lab experiments you have encountered in your college experience. Describe its value in learning concepts and/or hands on skills compared to other lab experiments.	Compare this lab experiment to other lab experiments you have encountered in your college experience. Describe its value in learning concepts and/or hands on skills compared to other lab experiments.	What was interesting/valuable about this lab experiment?
Do you have any other general ideas on how to improve the lab experience in all of MIE? (Ideas: different facilities, different offerings, something you need from TAs or professors, etc.)	What was interesting/valuable about this lab experiment?	What was interesting/valuable about this lab experiment?	What was the most challenging part of this experiment?
	What was the most challenging part of this experiment?	What was the most challenging part of this experiment?	
	Compare this lab experiment to other online activities of any kind. What sort of online class activities are more/less engaging or valuable?	Compare this lab experiment to other online activities of any kind. What sort of online class activities are more/less engaging or valuable?	

When survey data from previous terms was compared to newer data, labs were grouped based on concepts taught rather than title or subject of the lab. Thus, the pre-COVID pressure lab was compared to the post-COVID ultrasonic distance measurement lab as both were concerned primarily with calibration, accuracy, and precision. The dynamic temperature and wind tunnel labs were essentially unchanged throughout the various terms thus there was no need to group them any differently. The mechanical power lab that was in place prior to COVID was grouped with the solar power lab in the post COVID course since both labs cover design of experiments and the development of power curves. Similarly, the heat transfer in crossflow lab from before COVID was grouped with the thermodynamics lab developed for Fall 2020 as both labs centered around heat transfer concepts. The strain measurement lab and the data analysis lab which replaced it were too different from each other for easy comparison, thus these were considered individually.

Survey data gathered between Fall 2019 and Fall 2021 was analyzed by comparing the outcomes from the Likert scale questions over time with emphasis on terms where the percentage of students agreeing or strongly agreeing with a given statement changed markedly. Correlations between survey items were sought using the Pearson's product moment correlation analysis. Significant differences between terms were also analyzed using one-way ANOVA analysis ($\alpha = 0.05$). For the two terms that were administered in the hybrid mode, comparisons were also made between students who were fully on campus, fully at home, or partly on campus and partly at home (hybrid). This data has previously been presented in [1]. Open response questions were examined to determine common themes in terms of both the value of individual experiments and attitudes toward online/hybrid activities in general.

The questions to be answered by this research are:

1. Which student responses were most changed by the altered experiments?
2. Which aspects of the hybrid labs were different from either the previous or post COVID in person labs?
3. Were the new in person experiments seen to be an improvement over the previous in person experiments?
4. Are there any lessons to be learned that would ease the introduction of new experiments in the future?

Results

Comparison to previous surveys

The data shown in Figures 1-6 below represent the experiments immediately before, during, and after COVID. Fall 2019 and Spring 2020 had the same lab experiments, however the last two experiments were not performed in Spring 2020 due to the COVID shut down. As discussed previously, labs are grouped by concepts taught in places where the details of the lab changed. Data from the pre-COVID strain lab is therefore excluded from the comparison over time as the concepts covered in the previous experiments are now being performed as an in-class activity during lecture. Dotted lines indicate that a question was skipped during one or more semesters. Some questions which were only asked prior to or subsequent to COVID do not have data points for all terms.

Figure 1 shows the percentage of students who responded "agree" or "strongly agree" to the Likert scale questions for Lab 1. Note that the question "Was this lab supported by lecture" was not asked during Fall 2020. There was a rise in frustration and confusion during Fall 2020, which was the first term with the new Arduino based lab. The Fall 2020 and Spring 2021 courses were in the hybrid format, and the learning curve for instructor and students is shown in the decrease in the percentage of students who thought that the lab engaged all group members. However, using the survey feedback, the lab has steadily improved since then, becoming much less frustrating and much more helpful in engaging students and teaching course concepts. There was little change in student opinion about how much the lab helps them learn the calibration concepts and whether the lab was fully supported by the lecture portion of the course.

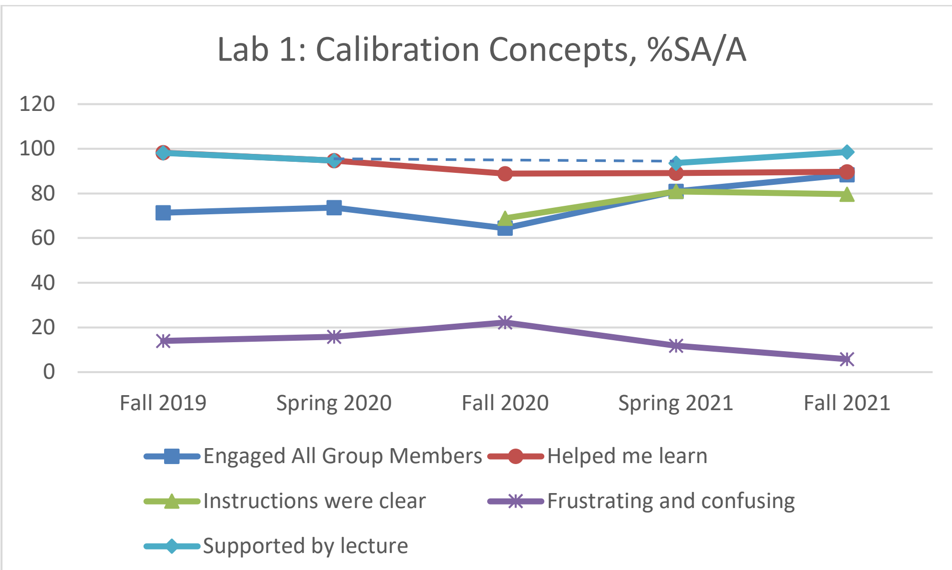

Figure 1: Percent of respondents choosing Strongly Agree or Agree for Lab 1 over time

Figure 2 shows the results for Lab 2. The lab experiments grouped under the heading 'Power & DOE' were somewhat different and occurred at different points during the term before and after COVID. Prior to COVID, students studied mechanical and electrical power using a bicycle powered generator. Lab groups were expected to determine what data needed to be collected to be able to answer the analysis questions, which required them to collectively design the procedure. The bicycle lab was the second to last lab in the course. This experiment was not performed during Spring 2020 due to COVID. After COVID, students studied electrical power generated by a solar cell under different conditions. They were required to do background research, identify variables, and design the experiment to answer analysis questions. The solar cell lab was the second lab in the post-COVID course. At this stage, some students were frustrated by the lack of structure, as this was often their first experience in designing experiments. This was shown in the increase of students who found the lab frustrating or confusing, and a fairly large percentage of students who found the instructions unclear. Refining the lab during Spring and Fall 2021 resulted in the lab being perceived as more helpful for learning and less confusing, however there is still work to be done in supporting DOE concepts in the lectures.

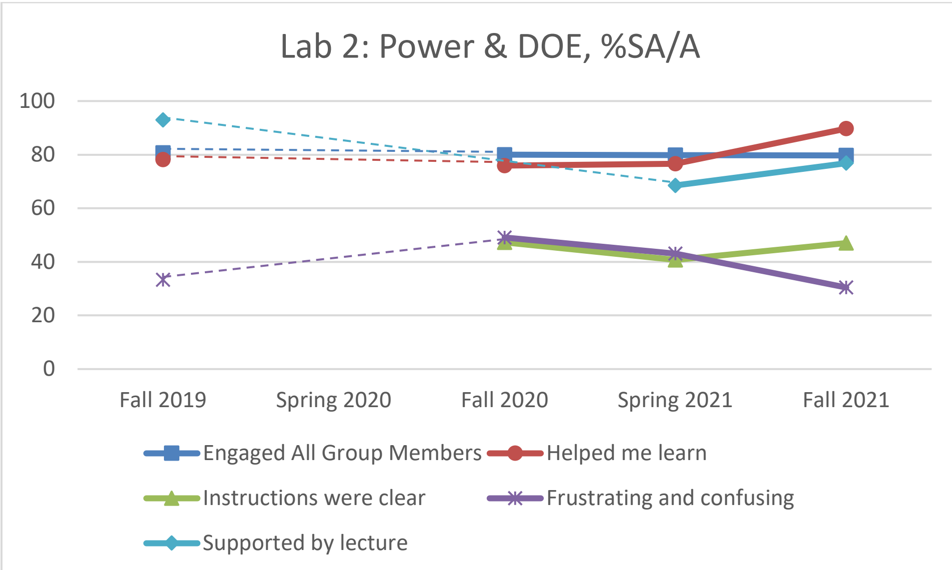

Figure 2: Percent of respondents choosing Strongly Agree or Agree for Lab 2 over time

The results for Lab 3 concerning dynamic temperature measurements are shown in Figure 3. This lab was essentially unchanged before and after COVID, with the major difference being the data acquisition equipment used. The percentage of respondents who thought the lab helped them learn and was supported by lecture has remained reasonably steady over time. The introduction of the Arduino hardware in Fall 2020 and its use in subsequent terms has improved the perception that the lab engages the students. Fall 2020 showed a large jump in the number of students who found the lab confusing. This was partly due to equipment, as certain Arduino modules from different manufacturers turned out to have different wiring. This was addressed in subsequent terms and the lab reports rewritten to improve clarity. As a result, the frustration level was reduced to nearly zero.

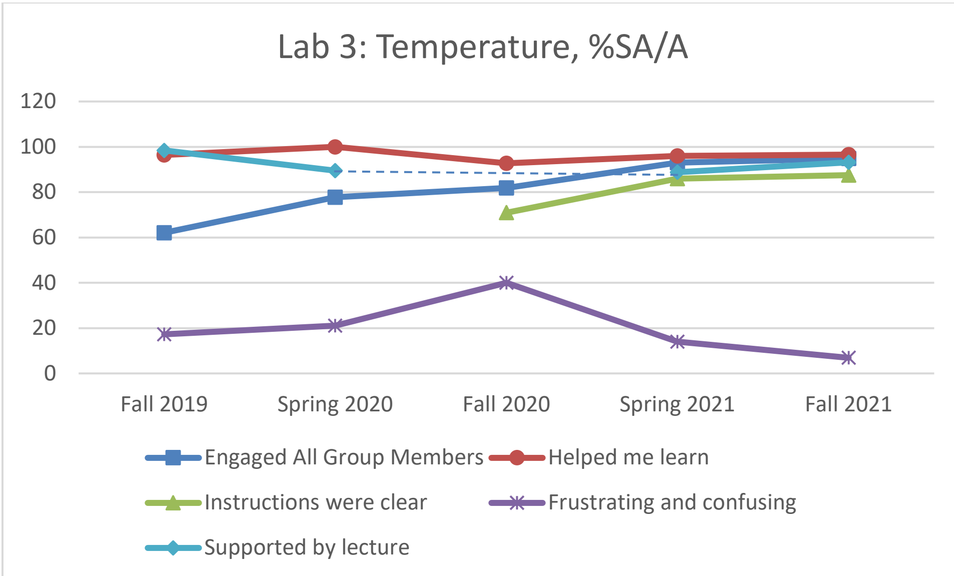

Figure 3: Percent of respondents choosing Strongly Agree or Agree for Lab 3 over time

Figure 4 shows the results for the data analysis lab that was not performed prior to COVID. The purpose of this lab was to gather data using an Arduino load cell and perform subsequent statistical data analysis and uncertainty analysis. This lab was largely seen as having clear instructions, being engaging, and helping the students learn from its introduction. The lab was found to be slightly more confusing in Fall 2021. This was a result of miscommunication during lecture about what supplies were needed for the lab. This will be clarified for Spring 2022.

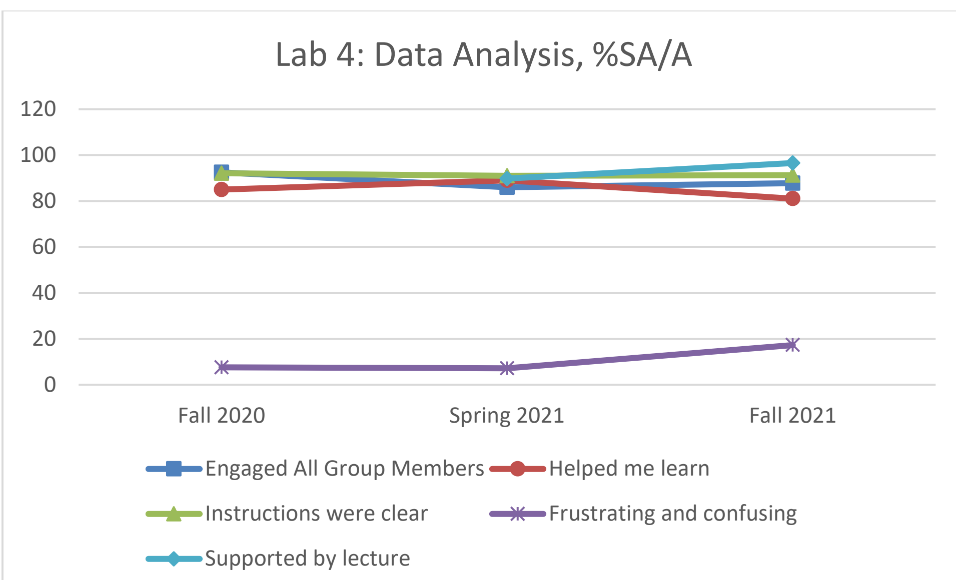

Figure 4: Percent of respondents choosing Strongly Agree or Agree for Lab 4 over time

The results for Lab 5 are shown in Figure 5. The goal of this lab has always been to provide students an opportunity to connect thermodynamics and heat transfer theory learned in previous classes to real world measurements. Prior to COVID this was accomplished by having the students study a heated cylinder in crossflow. The redesigned lab had the students comparing open and closed thermodynamic systems by performing energy and power balances. The first instance of this lab in Fall 2020 had some students gathering data on the open system remotely, while on campus students studied the closed system. This was initially quite difficult to convey, as shown by the large spike in student frustration. Subsequent refinement of the lab has reduced the frustration level and improved the perceived engagement. However, this lab still requires refinement as students still see the instructions as relatively unclear and are not always certain that it helps them learn.

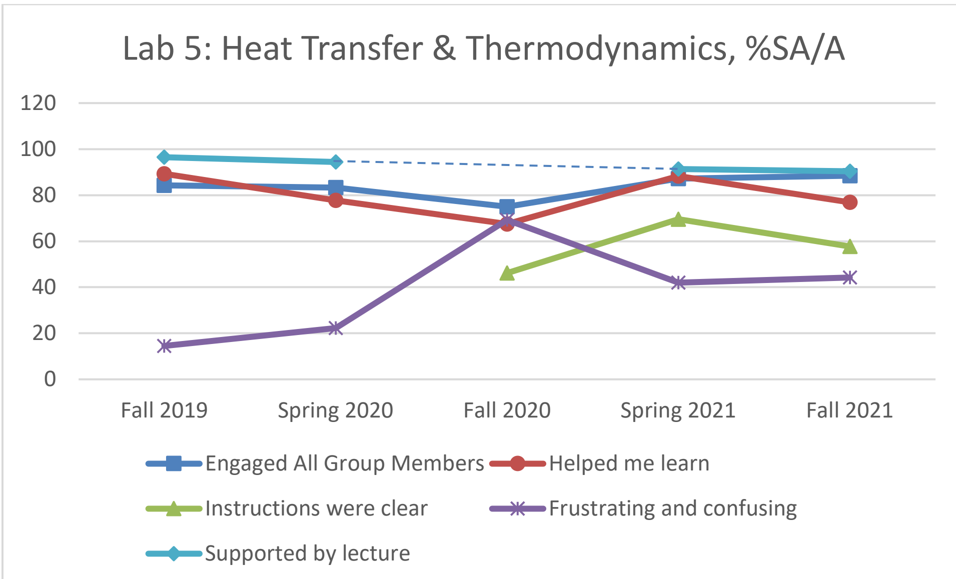

Figure 5: Percent of respondents choosing Strongly Agree or Agree for Lab 5 over time

Finally, Figure 6 provides the data for Lab 6: Wind Tunnel, which has also remained relatively unchanged before and after COVID. Due to the COVID shut down, this experiment was not performed during Spring 2020. This lab is seen as being well supported by lecture and helping students learn the material; these measures increased compared to the pre-COVID version. The first instance of the new lab experiment in Fall 2020 had the entire lab section work together to accomplish the lab. This resulted in many students not being able to actively participate as there is only one wind tunnel. During both hybrid terms remote students were connected to their in-class group members via Zoom. For Spring and Fall 2021, the lab was scheduled such that a maximum of 6 students were physically using the wind tunnel at any given time. This improved student engagement, and eventually reduced frustration as the lab was further refined.

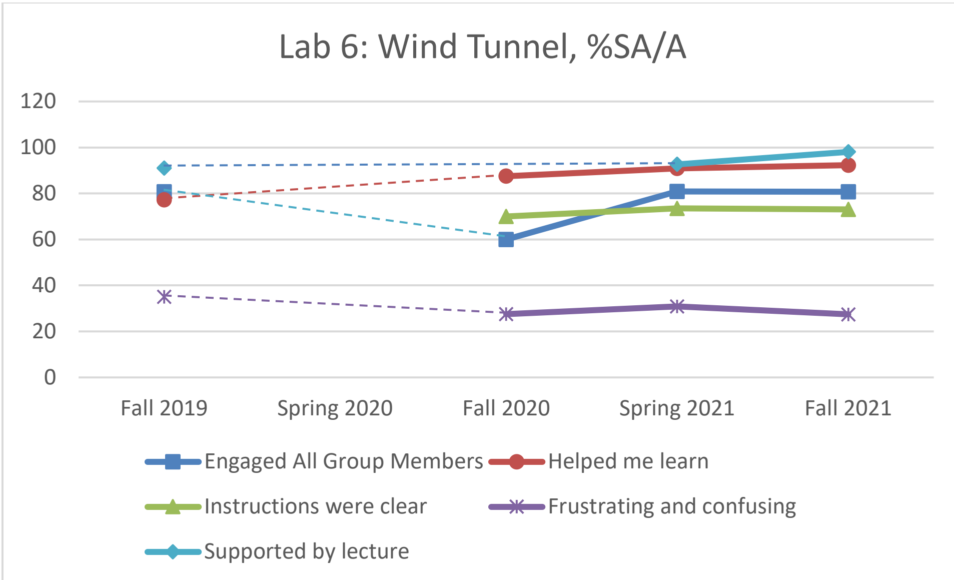

Figure 6: Percent of respondents choosing Strongly Agree or Agree for Lab 6 over time

Correlation Analysis

Correlations between survey items were sought using the Pearson's product moment correlation analysis. Survey results were compared by grouping related experiments together and then analyzing correlations for each term. Prior to COVID, a paper-based survey on all 6 labs was handed out in class during the last week of term. This was hastily shifted to an electronic form during Spring 2020 when the COVID shutdown occurred. This led to very low response rates in Spring 2020. Starting in Fall 2020, the survey was redesigned and issued using the course management system. A survey went out after labs 2, 4, and 6, with each survey requesting feedback on 2 experiments. As an incentive, 5 points of extra credit were awarded for completing the survey. Students used a separate email form to indicate that they had done the survey to maintain anonymity. Students during the hybrid terms were asked to indicate whether they were attending classes remotely, part time on campus, or fully on campus. These responses were assigned values of 0, 0.5, and 1, respectively, to indicate percentage of time spent on campus.

Table 4 shows the statistically significant correlations between survey items for the labs that taught calibration concepts. Labs in Fall 2019 and Spring 2020 had few statistically significant correlations. The most commonly correlated factor was whether students thought that they could apply the skills they learned in that lab to some other problem. It was also important that the labs were supported by the lecture. All the correlations for these first two terms were strong correlations. The first hybrid lab semester, Fall 2020, had only two statistically significant correlations. There was a moderately positive correlation between students who felt the lab helped them learn course concepts and those who thought the lab engaged all group members. There was also a moderate negative correlation between those who found the lab frustrating and confusing and those who thought the lab instructions were clear. Clear lab instructions also seem to make or break the student experience in Spring 2021, as the two statistically significant correlations were both related to clear lab instructions. This problem was remedied during Fall 2021 as there were no strong correlations with clear lab instructions and only a moderate correlation between the lab helping students to learn the course concepts and the lab engaging all students.

Table 4: Statistically significant correlations between survey items for calibration experiments

Calibration Lab (Pressure/Ultrasonic distance measurements)		
Fall 2019 (N=57)	**R**	**P (α = 0.05)**
Can apply to other problems/Helped me learn	0.94	P = 0.01
Helped me learn/interesting and engaging	0.91	P = 0.02
Can apply to other problems/Supported by lecture	0.89	P = 0.03
Spring 2020 (N=19)	**R**	**P (α = 0.05)**
Can apply to other problems/Helped me learn	0.98	P = 0.003
Can apply to other problems/Supported by lecture	0.97	P = 0.01
Supported by lecture/Helped me learn	0.90	P = 0.04
Fall 2020 (N=45)	**R**	**P (α = 0.05)**
Lab 1 helped me learn course concepts/Lab engaged all group members	0.58	P<0.001
Lab 1 was frustrating & confusing/Lab instructions were clear	-0.67	P<0.001
Spring 2021 (N=110)	**R**	**P (α = 0.05)**
The instructions were clear/Lab helped me learn	0.40	P<0.001
Frustrating & Confusing/Instructions were clear	-0.40	P<0.001
Fall 2021 (N=62)	**R**	**P (α = 0.05)**
Helped learn course concepts/Engaged all group members	0.41	P<0.001

The correlation analysis results for the labs which taught DOE and power measurements are provided in Table 5. There is no data for the Spring 2020 semester as this lab was cancelled due to the COVID interruption. As in the calibration experiments, having the information be perceived as applicable to other problems was correlated with several outcomes including engagement, whether the experiment helped teach course concepts, and whether the material was sufficiently supported in the lecture. Clear support and instruction in the lecture portion of the class was also highly correlated with student engagement and perceived learning value of the activity. These correlations were strong but were not highly statistically significant. During the first hybrid term in Fall 2020 frustration and confusion negatively impacted student perception of learning value and stemmed primarily from unclear instructions. Although only a moderate effect, it is evident that clear instructions are important for students to feel they are learning. The importance of clear instructions is also evident in the results from Spring 2021. Clear instructions were positively correlated with perception that the labs were helpful in learning course material and that the labs were supported by the lecture, as well as promoting engagement. However, frustrating and confusing experiments are still detrimental to student learning and are related to the quality of the lab handouts. Fall 2021 still showed a statistically significant relationship between frustration and clarity of instructions. However, this term also had positive correlations that indicated learning was best achieved when all lab members were engaged and the lab was clearly supported by lecture.

Table 5: Statistically significant correlations between survey items for Power/DOE experiments

Power & Design of Experiments (Mechanical/Solar)		
Fall 2019 (N=57)	**R**	**P(α = 0.05)**
Can apply to other problems/Helped me learn	0.98	P = 0.003
Supported by lecture/Interesting and engaging	0.98	P = 0.003
Can apply to other problems/Supported by lecture	0.94	P = 0.01
Can apply to other problems/Interesting and engaging	0.93	P = 0.02
Supported by lecture/Helped me learn	0.87	P = 0.05
Spring 2020 - No data		
Fall 2020 (N=55)	**R**	**P(α = 0.05)**
The instructions were clear/Lab helped me learn	0.43	P<0.001
Frustrating and confusing/Lab helped me learn	-0.46	P<0.001
Frustrating and confusing/Instructions were clear	-0.65	P<0.001
Spring 2021 (N=110)	**R**	**P (α = 0.05)**
Lab helped me learn/Engaged all group members	0.54	P<0.001
Supported by lecture/Helped me learn	0.53	P<0.001
Supported by Lecture/Instructions were clear	0.48	P<0.001
Instructions were clear/Lab helped me learn	0.45	P<0.001
Supported by lecture/Engaged all group members	0.4	P<0.001
Instructions were clear/Engaged all group members	0.37	P<0.001
Frustrating and confusing/Lab helped me learn	-0.34	P<0.001
Frustrating and confusing/Instructions were clear	-0.46	P<0.001
Fall 2021 (N=69)	**R**	**P (α = 0.05)**
Lab helped me learn/Engaged all group members	0.52	P<0.001
Supported by lecture/Helped me learn	0.49	P<0.001
Supported by Lecture/Instructions were clear	0.39	P<0.001
Frustrating and confusing/Instructions were clear	-0.59	P<0.001

Table 6 shows the results from the lab concerning dynamic temperature which did not change significantly before, during, or after COVID. Once again, results from Fall 2019 and Spring 2020 indicate a strong preference for activities that could potentially be applied to other problems. One interesting result was the highly negative correlation between frustration and whether the students found the experiment interesting and engaging seen in Fall 2019. It is difficult to know whether this frustration was due to confusing lab handouts or some other factor due to the survey questions asked that term. In Fall 2020 three of the four statistically significant correlations had to do with whether the lab helped them learn material. This was positively associated with clear lab instructions and group member engagement but negatively associated with frustration. Neither Spring 2021 nor Fall 2021 had any statistically significant correlations with frustration and confusion. It appears this was accomplished by improved connection between the lecture and the experiments combined with clearly written instructions.

Table 6: Statistically significant correlations between survey items for Temperature experiments

Temperature Lab		
Fall 2019 (N=57)	**R**	**P (α = 0.05)**
Can apply to other problems/Supported by lecture	0.99	P = 0.001
Can apply to other problems/Helped me learn	0.92	P = 0.03
Frustrating and confusing/Interesting and engaging	-0.93	P = 0.03
Spring 2020 (N=19)	**R**	**P (α = 0.05)**
Supported by lecture/Helped me learn	0.95	P = 0.02
Interesting and engaging/Helped me learn	0.94	P = 0.02
Can apply to other problems/Supported by lecture	0.91	P = 0.03
Fall 2020 (N=55)	**R**	**P (α = 0.05)**
Instructions were clear/Lab helped me learn	0.5	P<0.001
Lab helped me learn/Engaged all group members	0.41	P = 0.002
Frustrating and confusing/Instructions were clear	-0.48	P<0.001
Frustrating and confusing/Lab helped me learn	-0.42	P = 0.001
Spring 2021 (N=101)	**R**	**P (α = 0.05)**
Supported by lecture/Instructions were clear	0.48	P<0.001
Lab helped me learn/Engaged all group members	0.44	P<0.001
Instructions were clear/Lab helped me learn	0.42	P<0.001
Instructions were clear/Engaged all group members	0.37	P<0.001
Supported by lecture/Lab helped me learn	0.37	P<0.001
Fall 2021 (N=58)	**R**	**P (α = 0.05)**
Supported by lecture/Lab helped me learn	0.47	P<0.001
Lab helped me learn/Engaged all group members	0.37	P = 0.004
Supported by lecture/Engaged all group members	0.33	P = 0.01

The labs addressing heat transfer and thermodynamics had many significant correlations as shown in Table 7. In Fall 2019 there were three large negative correlations that stood out. All three of these related to the labs being frustrating and confusing. Much of this problem stems from the fact that not all students have necessarily completed heat transfer by the time they reach Measurements and Analysis. The frustration level is naturally higher among those who either have not taken the heat transfer class or are taking it concurrently. There was a correlation of 1.0 between students who found the class the lab interesting and engaging and those who felt it helped them learn. Heat transfer and thermodynamics are two courses that have no other lab experiences except what students see in Measurements and Analysis. Provided the instructor gives enough information during lecture to help those who have not taken heat transfer yet, this lab seems to be appreciated for giving students a chance to put these theoretical concepts to the test. This may also account for why the survey question about applying skills to other problems is correlated with many other questions in both Fall 2019 and Spring 2010. Fall 2020 showed a rise in frustration and confusion which negatively impacted both engagement and the perception that course concepts were being learned. This lab was rather involved and difficult and was perhaps not as well conveyed to the remote students as to the on-campus students. Moreover, the insulated boxes built for this experiment were not insulated sufficiently and did not provide results that clearly demonstrated the concepts. Two things were fixed during Spring 2021 that improved the situation somewhat. The boxes were insulated more thoroughly which gave more realistic data. Also, in Fall 2020 concerns were raised by the course technician about the ability of students to build and operate the Arduino circuit for this lab. Because of these concerns the circuit was built and provided by the technician for each lab group in the on-campus group. In Spring 2021 the students built the circuit themselves. This increased the number of positive correlations with engagement. Fall 2021 still had some students who were frustrated by unclear instructions. However, a larger number of students found the instructions clear and the lab valuable in learning course concepts.

Table 7: Statistically significant correlations between survey items for Heat Transfer/ Thermodynamics experiments

Heat Transfer/Thermodynamics Labs		
Fall 2019 (N=57)	**R**	**P (α = 0.05)**
Interesting and engaging/Helped me learn	1	P<0.001
Can apply to other problems/Helped me learn	0.99	P<0.001
Can apply to other problems/Interesting and engaging	0.98	P = 0.003
Supported by lecture/Helped me learn	0.96	P = 0.004
Can apply to other problems/Supported by lecture	0.96	P = 0.004
Supported by lecture/Interesting and engaging	0.93	P = 0.02
Can apply to other problems/Frustrating and confusing	-0.92	P = 0.02
Frustrating and confusing/Helped me learn	-0.89	P = 0.04
Supported by lecture/Frustrating and confusing	-0.89	P = 0.04
Spring 2020 (N=19)	**R**	**P (α = 0.05)**
Supported by lecture/Interesting and engaging	0.96	P = 0.009
Interesting and engaging/Helped me learn	0.94	P = 0.01
Can apply to other problems/Interesting and engaging	0.93	P = 0.02
Can apply to other problems/Supported by lecture	0.9	P = 0.04
Fall 2020 (N=40)	**R**	**P (α = 0.05)**
Lab helped me learn/Engaged all group members	0.56	P<0.001
Instructions were clear/Lab helped me learn	0.51	P<0.001
Instructions were clear/Engaged all group members	0.33	P = 0.04
Frustrating and confusing/Lab helped me learn	-0.37	P = 0.01
Frustrating and confusing/Engaged all group members	-0.38	P = 0.01
Spring 2021 (N=70)	**R**	**P (α = 0.05)**
Supported by lecture/Instructions were clear	0.59	P<0.001
Instructions were clear/Lab helped me learn	0.55	P<0.001
Supported by lecture/Lab helped me learn	0.45	P<0.001
Supported by lecture/Engaged all group members	0.4	P<0.001
Lab helped me learn/Engaged all group members	0.39	P<0.001
Instructions were clear/Engaged all group members	0.33	P = 0.005
Fall 2021 (N=52)	**R**	**P (α = 0.05)**
Lab helped me learn/Engaged all group members	0.47	P<0.001
Supported by lecture/Instructions were clear	0.42	P = 0.002
Supported by lecture/Lab helped me learn	0.4	P = 0.003
Instructions were clear/Lab helped me learn	0.37	P = 0.008
Frustrating and confusing/Instructions were clear	-0.54	P<0.001

Finally, Table 8 shows the significant correlations for the wind tunnel lab. This lab remained essentially unchanged before, during, and after COVID, however it was not performed during the Spring 2020 term. In Fall 2019 students saw this lab as generally supported by lecture, applicable to other problems, and engaging. As the department is developing an Aero/Astro minor, many students are becoming interested in wind tunnel testing for various projects. This experiment was quite difficult to adapt to the hybrid model, as there is only one wind tunnel and there is no way to easily simulate this at home. Technician concerns led to the Arduino circuit and sensors being set up in advance for the on-campus experience. This seems to have reduced the engagement as there were fewer positive correlations with engagement for this term. An interesting observation was that this was the only term that had any correlations with students being on or off campus. Students who were completely on campus seem to have found the instructions to be clearer, were convinced of the learning value of the experiment, and were less frustrated and confused than either the hybrid or completely remote students. For Fall 2020 remote students were able to participate both by being on Zoom with their team while the experiment was being performed on campus and by being encouraged to design their own wind turbine at home using a small motor provided with the lab kit. Students were asked to use their own creativity to determine ways to measure the revolutions per minute while using the Arduino to measure voltage output. Most at home students were not successful at this the first time but this turned out to be due to a confusing circuit diagram for that lab. Once the circuit diagram was redesigned for Spring 2021 and beyond, the frustration levels seem to decrease. Engagement levels were improved in Spring 2021 and Fall 2021 after the scheduling for the lab was changed as explained previously. Some improvements to the lab handouts made after Spring 2021 apparently made things slightly more confusing in Fall 2021 because there is a moderate but significant correlation between frustration and confusion and lab handout clarity.

Table 8: Statistically significant correlations between survey items for Wind Tunnel experiments

Wind Tunnel Lab		
Fall 2019 (N=57)	**R**	**P (α = 0.05)**
Interesting and engaging/Helped me learn	0.98	P = 0.005
Can apply to other problems/Interesting and engaging	0.98	P = 0.005
Can apply to other problems/Helped me learn	0.97	P = 0.006
Can apply to other problems/Supported by lecture	0.95	P = 0.01
Supported by lecture/Interesting and engaging	0.91	P = 0.03
Spring 2020 (No data)		
Fall 2020 (N=40)	**R**	**P (α = 0.05)**
Instructions were clear/Lab helped me learn	0.58	P<0.001
Lab helped me learn/Engaged all group members	0.57	P<0.001
Instructions were clear/Completely on campus	0.35	P = 0.03
Lab helped me learn/Completely on campus	0.34	P = 0.03
Frustrating and confusing/Completely on campus	-0.33	P = 0.03
Frustrating and confusing/Instructions were clear	-0.55	P<0.001
Spring 2021 (N=70)	**R**	**P (α = 0.05)**
Supported by lecture/Lab helped me learn	0.71	P<0.001
Supported by lecture/Instructions were clear	0.67	P<0.001
Lab helped me learn/Engaged all group members	0.56	P<0.001
Instructions were clear/Lab helped me learn	0.53	P<0.001
Instructions were clear/Engaged all group members	0.43	P<0.001
Supported by lecture/Engaged all group members	0.38	P = 0.001
Fall 2021 (N=52)	**R**	**P (α = 0.05)**
Lab helped me learn/Engaged all group members	0.58	P<0.001
Supported by lecture/Lab helped me learn	0.53	P<0.001
Instructions were clear/Lab helped me learn	0.47	P<0.001
Instructions were clear/Engaged all group members	0.36	P = 0.008
Frustrating and confusing/Instructions were clear	-0.36	P = 0.008

ANOVA Comparison of Survey Items

ANOVA analysis was used to determine if there were statistically significant differences between survey items for the hybrid labs and the new on campus labs. Only questions common to all three terms were examined. For Lab 1 statistically significant differences were found for the question “Lab 1 engaged all group members” (P<0.001) and the question “Lab 1 was frustrating or confusing” (P=0.01). The first hybrid lab in Fall 2020 was significantly less engaging then the subsequent two terms. The Fall 2020 lab was also more frustrating and confusing than the other two. This is not completely unexpected as new labs often have some growing pains. Lab 2 showed no significant difference between the three terms. For Lab 3 there were significant differences for the questions “Lab 3 engaged all group members” (P=0.03), “Lab 3 helped me learn course concepts” (P=0.03), “The instructions for Lab 3 were clear”

(P=0.03), and “Lab 3 was frustrating and confusing” (P=0.005). The Fall 2020 term was the outlier in all cases for Lab 3. This was interesting as this was a lab that had been unchanged for many years. However, confusion over the provided Arduino circuit diagram and code coupled with some equipment issues made the lab artificially difficult. This was rectified in Spring and Fall 2021 by redesigning the circuit diagram, allowing students to build the circuit themselves, and ensuring that only one manufacturer was used for all Arduino modules to prevent differences in the expected pin-outs. Labs 4 and 6 had no statistical differences between the terms. For Lab 5 the question “The instructions for Lab 5 were clear” (P = 0.003) was the only one with a statistically significant difference. Again, the outlier was Fall 2020. The combined data clearly shows that the first hybrid term, despite being designed over several months, did not have all the potential problems smoothed out.

Student comments

Student comments from the surveys were analyzed to determine any common themes and to see how those themes changed over time. Examining responses for all the terms showed that the main themes were ‘Course concepts’ – relating to whether the lab was helpful in helping the students learn course concepts, ‘Hardware/Coding – relating to data acquisition hardware and/or software, ‘Teamwork’ – relating to working with other students, ‘Instructions’ – relating to clarity of instructions, ‘Sensors/Equipment’ – relating to physical setups and sensors, ‘Writing’ – relating to lab reports, and ‘Other’ – which includes comments that do not easily fit into one of the other categories.

Table 9 below shows the results from the pre-COVID labs in terms of the percentage of questions that fell into each category. These two terms did not have the same questions as subsequent terms. The questions asked were “Can you think of any topics/experiments you would like to see added to Measurements and Analysis?” and “Do you have any other general ideas on how to improve the lab experience in all of MIE?” Although the second question was meant to solicit responses about the department in general, most of the responses related to the Measurements and Analysis course specifically. These questions were characterized as expressing sentiments that fit into the idea of ‘What was interesting/valuable about this lab experiment?’ and those that fit into ‘What was the most challenging part of this experiment?’ These questions were then coded like the other terms. Although the questions do not allow for a direct comparison, some patterns did emerge. In both terms, most of the positive comments described the labs as positively influencing the learning of course concepts. Coding, which at the time meant programming in LabView, was found as challenging in 30% and 50% of the responses, respectively. Writing and teamwork were mentioned in a relatively small number of responses. Sensors and equipment were generally found to be viewed more positively than negatively. Instructions also did not seem to be a major benefit or detriment. Many of the responses in the ‘other’ category related to the speed of lab grading or the utility of course information for other situations.

Table 9: Comparison of percentage of open responses in various themes in pre-COVID labs

Fall 2019	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team-work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Writing (%)**	**Other (%)**
% Interesting	60	0	0	13	33	0	20
% Challenging	22	30	7	15	15	7	35
Spring 2020	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team-work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Writing (%)**	**Other (%)**
% Interesting	80	0	0	20	40	0	0
% Challenging	33	50	17	17	17	0	33

The open comment results from Fall 2020, the first hybrid lab, are shown in Table 10. Once again, the table shows the percentage of responses to a question that fell into each category. For Labs 1, 3, 4, and 5, the largest percentage of responses to the question "What was interesting/valuable about this lab experiment?" had to do with course concepts. Lab 5, which covered thermodynamics and heat transfer measurements, was seen by students as particularly helpful for learning these difficult topics. Sensors and other equipment were also seen as contributing to interest and engagement levels. However, sensors and equipment also represented a large percentage of the responses about what was challenging in the various labs. Two typical, contrasting student comments include:

"I liked learning more about the Arduino and its sensors; specifically I never used the ultrasonic range sensors before so that was nice to learn how they work."

"The at home portion of the lab was very challenging just getting the equipment working. My group members were unable to get their equipment to work for the at home portion of the lab."

The at-home portions of the experiments were appreciated by many students, as most other lab classes had resorted to having the students watch videos of experiments. However, as evidenced by the comment above, difficulties with the at-home equipment were often hard for the students to resolve on their own. Encouragingly, despite a few complaints about working across time zones, the number of responses relating to teamwork was low, indicating a reasonable degree of success in connecting the on campus and remote students.

Table 10: Comparison of percentage of open responses in various themes in Fall 2020 labs

Fall 2020 Interesting and Engaging	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Other (%)**	**Writing (%)**
Lab 1	54	23	3	3	26	18	0
Lab 2	49	6	0	4	51	11	0
Lab 3	56	2	0	0	46	10	0
Lab 4	57	6	3	0	17	29	0
Lab 5	65	6	0	3	13	23	0
Lab 6	36	3	3	0	58	30	0
Fall 2020 Challenging	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Other (%)**	**Writing (%)**
Lab 1	50	21	2	2	24	17	0
Lab 2	41	9	4	9	24	26	0
Lab 3	6	24	2	6	56	26	0
Lab 4	47	26	3	3	15	12	3
Lab 5	25	11	0	14	47	33	3
Lab 6	18	27	9	3	45	36	3

Feedback from Fall 2020 was used to improve the course for Spring 2021. Results from comment analysis for Spring 2021 are shown in Table 11. Challenges related to course concepts decreased for all labs except for Labs 3 and 6. Challenges related to sensors and equipment decreased slightly for most labs, and challenges relating to instructions decreased or remained roughly the same. This was encouraging, as clear instructions are correlated with various positive factors, as discussed above. Some labs showed an increase in challenges due to Arduino hardware and coding issues. This was to be expected, as an effort was made not to set up the Arduino circuits in advance, but to have the students do it themselves. This change elicited both positive and negative comments:

"*Using Arduino and being able to complete the lab independently at home helped me feel more confident about using Arduino for experiments in the future.*"

"I found the initial Arduino programming to be the most challenging part of this experiment. This is because I didn't initially realize I needed to download something from the internet before using the lux sensor."

An additional teaching assistant was hired for this course whose job was to improve the Arduino codes and circuit diagrams, and to provide office hours solely devoted to Arduino problems. Students who took advantage of this resource seemed to profit from the experience, but not all students did so. Overall this offering seemed to fix some of the problems experienced in Fall 2020, but not all of them.

Table 11: Comparison of percentage of open responses in various themes in Spring 2021 labs

Spring 2021 Interesting and Engaging	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Other (%)**	**Writing (%)**
Lab 1	49	27	10	3	21	18	0
Lab 2	41	13	5	0	42	21	0
Lab 3	39	5	1	0	39	35	0
Lab 4	36	11	0	0	22	43	0
Lab 5	67	5	2	0	10	22	0
Lab 6	42	14	7	7	27	24	8
Spring 2021 Challenging (%)	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Other (%)**	**Writing (%)**
Lab 1	8	20	25	4	20	24	8
Lab 2	32	22	7	10	12	29	3
Lab 3	15	14	5	7	21	42	5
Lab 4	24	33	2	0	4	39	1
Lab 5	40	13	6	6	26	23	8
Lab 6	10	15	3	3	31	45	0

Finally, Table 12 presents the analysis of student comments from Fall 2021, where the hybrid experiments were converted back to on-campus experiments. Positive comments about course concepts increased in all labs. A particularly encouraging result was for Lab 5. This is a particularly difficult lab, both in terms of concepts and in terms of equipment. Although sensors and equipment were still found to be a source of some difficulties, the percentage of comments that indicated that the lab helped learn course concepts remained at a relatively high 67%. Hardware and coding concerns elicited fewer positive and negative responses overall. This may be due to an increase in the number of second year students taking the course. Students with many AP credits may take this course as early as their second year. These students have used Arduino much more recently than the juniors or seniors. However, these younger students tend to struggle with writing procedures and open-ended labs in general. Two contrasting views on this subject include:

"*I think the most valuable part of this lab was coming up with the procedure itself. Since solar cell I(V) and power curves aren't necessarily familiar concepts, the lab required external research to complete successfully."*

"Even though designing the experiment was the most interesting, I think it also was the most challenging part, as it was just so open to what we could have done."

To combat this, future terms will provide further explicit discussion about the aim of these open-ended labs along with more clearly defined boundaries for the problems.

Table 12: Comparison of percentage of open responses in various themes in Fall 2021 labs

Fall 2021 Interesting	Course concepts (%)	Hardware/ Coding (%)	Team work (%)	Instructions (%)	Sensors/ Equipment (%)	Other (%)	Writing (%)
Lab 1	65	13	4	0	29	16	1
Lab 2	52	4	0	1	52	20	0
Lab 3	34	4	0	0	59	23	0
Lab 4	54	5	2	0	13	45	2
Lab 5	67	4	2	0	11	29	2
Lab 6	24	0	7	0	71	24	0
Fall 2021 Challenging	**Course concepts (%)**	**Hardware/ Coding (%)**	**Team work (%)**	**Instructions (%)**	**Sensors/ Equipment (%)**	**Other (%)**	**Writing (%)**
Lab 1	13	19	0	7	25	30	14
Lab 2	32	16	4	10	19	33	0
Lab 3	21	21	2	7	16	44	0
Lab 4	24	21	5	7	16	34	2
Lab 5	38	11	0	5	30	30	7
Lab 6	8	23	8	6	46	33	0

Discussion

Prior to COVID, all labs were perceived as being clearly connected to the lecture portion of the class. This is encouraging as the course is designed for the lecture and experimental parts of the class to be interlocked. Students learn and practice the concepts in class the week before the lab, then complete the pre-lab homework which is returned by Monday of the week the experiment occurs, followed by demonstrating their knowledge in the laboratory. Except for the calibration and temperature labs, all labs had greater than 80% of the respondents agree or strongly agree that the labs engaged all group members. Similarly, all pre-COVID labs had 80% or greater agreement that the labs helped them learn the material. Frustration levels never rose above 40% agreement.

The stresses caused by COVID can be seen in the survey results for Spring 2020. In the four labs performed that term, frustration levels increased over the previous term. The labs were still seen as supported by lecture and engaging all group members, and the percentage of students who thought the lab helped them learn either decreased slightly or increased by a noticeable amount. In general, this term was going very well until the COVID interruption, although the student uncertainty and stress levels were evident.

Introducing new experiments is generally accompanied by unforeseen complications, despite testing prior to the start of term. Some problems were caused by tension between the instructor's desire for heavy student involvement and the course technician's fears of confusion and broken equipment. This led the technician to set up some of the circuits and hardware prior to lab, leaving the students with less to do and making it difficult for the students to troubleshoot circuits they had not built. Other unforeseen difficulties came from the sensors ordered for the lab kits. Certain sensors needed to be soldered prior to inclusion in the kits, which occasionally led to sensors failing due to poor solder joints. The thermocouple sensors, which were used for several labs, were difficult to obtain in sufficient numbers from the same vendor. It was not immediately clear that the pin-out connections were different between sensors from different vendors, leading to circuits that didn't work. This contributed to higher than usual frustration levels in labs which were dependent on thermocouples, most notably Lab 5. It was also evident that the new lab handouts, despite revisions based on input from the technician and the teaching assistants, were confusing to the students in many cases, leading to a perception that the labs were less valuable in helping students learn the course concepts. Sensor and Arduino difficulties also tended to lead to at-home students being less engaged in the process, which was frustrating for all team members. Lab 2, which was meant to step students through a detailed design of experiments exercise, was particularly difficult for students as many had never done this before and the instructions were perceived as confusing. There were some bright spots, however. Lab 4, a new lab focusing on data analysis, was well received and led to far fewer complaints about the need for practice in those concepts. There were also improvements in engagement for Lab 3, which had historically been low in perceived engagement levels.

Spring 2021 demonstrated that relatively small changes can have a noticeable impact on student perceptions. Frustration decreased, sometimes markedly, for all labs except Lab 6, which only had a slight increase. That frustration was generally due to difficulties with equipment. All labs except Lab 2 showed an increase in agreement that the instructions were clear. Lab 2 is rather difficult to convey to the students in a way that provides enough guidance without detracting too much from the goal of students researching and designing their own experimental procedures. Engagement increased or stayed relatively level for all labs, with over 80% of the respondents agreeing. This was also the case for students' perception that the lab helped them learn course principles. Perceived connection to the lecture varied a bit more, decreasing in some labs and increasing in others. However, agreement on this measure never dropped below 75%. Paradoxically, students preferred less guidance in many of the experiments. This falls in line with a common pre-COVID complaint that too much of the equipment was set up in advance, robbing the students of hands-on experiences. The reduced guidance and increased dependence on students performing the setup themselves was deliberate, but also a result of necessity. The previous technician had left the department, and no replacement was hired until after Spring 2021. This led to an increased workload for the instructor, but also forced the instructor to step back and see what the students could and couldn't figure out. Students both at home and on campus were surprisingly adept at most tasks. Additional support from the Arduino TA, combined with improved lab TA training, provided guidance while still allowing the students to have as much control as possible.

The return to full time on campus instruction in Fall 2021 allowed comparison between the previous on-campus labs and the new experiments. Labs 1, 2, 3, and 6 showed improvement in all survey measures compared to the previous term, with some measures reaching all time high levels. Lab 4 had slight increases in frustration and slight decreases in whether the lab helped them learn. The frustration in this case stemmed from a misunderstanding among a portion of the students on what students needed to supply for the lab versus what was provided by the instructor. Also, the lab handout discussed strain in more detail than was necessary for that experiment. Despite this, the levels of agreement for all survey items were largely favorable. Lab 5 continued to be somewhat difficult for the students. The lab was perceived as supported by lecture and highly useful for experiencing principles that had only been taught as theory in previous courses. The sheer number of sensors required remains a source of frustration. Also, the experiment is prone to errors, which decreases the students' perception that the lab helps them learn the material. This is in part deliberate, as students are asked to identify potential sources of error and explain why theory and reality are not lining up perfectly. But again, younger students with fewer open-ended experiences tend to get frustrated when answers seem too far off from what is expected. An additional problem for Fall 2021 was that lab groups worked on the open and closed system in series, despite being urged multiple times to split the group and perform the work in parallel. This increased frustration due to running out of time in the lab session.

The most noticeable difference between the pre- and post-COVID experiments was the students' reaction to the data acquisition hardware and software. The LabView program is relatively difficult to learn in a short time. Although the students spent an entire lab session devoted to learning the basics of the program, followed by additional information in lecture, they still struggled with developing their own Virtual Instruments (VI). Difficulties with running the software over the VPN, interfacing with the data acquisition hardware, and lack of compatibility with Macintosh computers meant that many students could not effectively work on the programming outside of class time. Because of these difficulties, the technician provided laptops with working VIs in lab. While this meant that the students could take data, it also meant that they had no incentive to put in the effort to learn the program.

LabView had been a part of the course for more than a decade due to faculty perception that it was a vital skill for future work. Although that may have once been the case, there has been a dramatic increase in the use of Arduino sensors at universities and in industry. Moreover, the first year engineering curriculum relies heavily on Arduinos for experimentation. Students enjoy working with this platform and had been disappointed in the past that there were few opportunities to work with it after their first year. While there is a bit of a learning curve for students who have not used Arduino in several years, the ability to build their own sensor arrays for lab and for independent projects has been highly beneficial. Since the equipment is generally low cost and easily obtainable, this facilitated at-home experimentation during the hybrid terms. It also means that spare parts are easily stockpiled, which means that students who develop sensor issues on campus can get a new sensor or Arduino board to troubleshoot the problem.

Finally, the use of Arduino equipment produces positive interdependence for many students. Younger students, who often feel a bit intimidated by a perceived lack of knowledge compared to older students, are generally the ones who have more recent Arduino experience. The combination of students with a stronger theoretical background with students who have recent hardware and software experience leads to engaged and effective lab teams.

Conclusions and Recommendations

Lab courses are more effective when students are physically interacting with equipment and are in control of lab outcomes. The Measurements and Analysis course at Northeastern University was designed to promote hands on and open-ended experimentation. Despite deliberately designing the course for this purpose, pre-COVID labs were not perfect. Difficulties with data acquisition software and hardware, unnecessary setup of equipment that the students could handle themselves, and inconsistent connection between the lecture and lab portions of the course all needed improvement.

The need to pivot to hybrid labs posed both a challenge and an opportunity for course improvement. While other instructors, including some at Northeastern University, decided to rely on recorded experiments and instructor provided data, the author felt that this would negatively impact the unique nature of the course. Switching to small, low cost Arduino sensors and building on previous knowledge allowed for all students to actively experiment, regardless of location. Isolation and disconnection from the class was minimized by requiring on and off campus students to work together to gather data and complete experiments. After the initial semester, in which several weaknesses of the new labs were exposed, improvements were made that enhanced student learning and engagement in the topics. Moving the labs back on campus has proven to be nearly seamless. Additionally, the nature of the equipment allows for the accommodation of small numbers of one-off remote students. As an anecdotal observation, the author has noticed increased use of and skill in Arduino for capstone design, which typically occurs the year following Measurements and Analysis.

This study has led to the following recommendations for working with remote students and introducing new lab experiments:

- Active hands-on experimentation is possible for remote students outside of electrical and computer-based classes.
- Grouping remote and on-campus students to work on experiments promotes active participation by all students.
- Undergraduate students are capable of many experimental tasks and can design their own procedures given sufficient guidelines and support.
- Low-cost sensors promote hands-on learning with fewer consequences in the case of student errors.

- Clear instructions and expectations are paramount for any lab course but are particularly important when major changes are made. Extra scrutiny of handouts, supporting lectures, and TA/technician duties is vital.
- Detailed examination of student survey feedback allows for rapid improvement of course difficulties, and this improvement is noticed by the students.

The educational disruption due to COVID has been a severe trial for instructors and students alike. However, it has also been the catalyst for outside-the-box solutions to instructional challenges. These solutions can be the foundation of future, long-lasting improvement to the learning value of lab courses.

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