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Introducing Experimental Design to Promote Active Learning

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Abstract

In this study, a new experimental design format for a mechanical engineering junior laboratory course at Columbia University is proposed and implemented. The goal of the change in format is to transition the course from a passive learning environment to an active learning space. Using a scaffolded learning approach, existing experiments were replaced by modules that guided students towards the creation of their own novel experiments. In these novel experiments, they identified a mechanical engineering problem, conducted background research, and proposed a hypothesis. They then constructed their experimental apparatuses, conducted their experiments, and used statistical techniques to analyze their results. The course culminated in a conference-style paper and presentation to showcase their findings. The impact of the redesign was measured using pre- and post-surveys that evaluated key learning objectives as well as the lifelong learning question set. Overall, the modification led to significant improvements in student learning.

Introduction

In mechanical engineering education, introductory lab courses play a crucial role in exposing students to the breadth of topics, experimental techniques, and apparatuses in the field. They have played a long-standing role in rounding out the practical portion of an engineer's education [1]. These introductory courses are active, collaborative, cooperative, and problem-based in their very nature [2]. Students are in a hands-on laboratory space, working to collect data necessary to test an experimental hypothesis. Prince [2] defines *active learning* as "any instructional method that engages students in the learning process." Laboratory classes certainly fall under that umbrella.

The goal of active learning in a mechanical engineering laboratory context is multi-fold. The course should teach students to utilize and characterize a variety of lab apparatuses to test mechanical engineering hypotheses. It should also enable them to test fundamental mechanical engineering concepts including stress-strain analysis, heat-transfer, and material properties. Just as importantly, it should teach students to *identify* and *formulate* a mechanical engineering problem that requires experimental testing. Recognizing that in the "real world," problems and solutions are not neatly defined, it should teach students to conduct background research, define a problem, develop a hypothesis, design their own experiments, conduct their own analysis, and be able to create a conference-style lab report that succinctly summarizes their efforts.

With such a large variety of course goals, it is no surprise that the nature of laboratory active education can take many forms. In its most traditional form, the “active" nature of the course is primarily superficial. For each experiment, students are given source materials and a detailed set of instructions that walks them through, step-by-step, how to complete the lab. After each experiment, the students submit lengthy reports where they detail their methodology and analysis. While this approach has the benefit of allowing students to use a variety of sophisticated pieces of equipment, the rote nature of following these steps can inhibit learning. In “Understanding by Design," Wiggins and McTighe note that when students understand the purpose of what they are learning, they are more engaged and focused [3]. This larger purpose can be lost when bogged down in the details of calibrating and using advanced equipment before a student is ready. Furthermore, this format provides no opportunity for experimental design.

In recent years, a variety of instructors have excelled past the traditional lab class to improve student learning. In some universities, instructors have focused on inquiry based learning [4, 5]. In those approaches, students are given an experimental goal, but they are given great latitude in how they arrive there. Students are encouraged to develop their own pathways to that goal instead of following a detailed recipe. Others have introduced scaffolded learning to build from basic principles to more open-ended experiments [6, 7]. In scaffolding, students are given reasonable steps that guide them towards the course learning goals [7].

A promising addition to these techniques is the introduction of experimental design. Design courses have students take ownership over the direction of a project, placing them directly into the educational process [8]. That ownership leads to a sharp improvement in student ability to solve open-ended problems and work with others [8]. In the context of laboratory courses, it could provide an avenue to take students beyond just conducting existing experiments, but into the realm of creating their own.

In this paper we take lessons from inquiry-based learning, scaffolding, and designing to modify a mechanical engineering lab course at Columbia University and assess its impact. An existing junior mechanical engineering lab course was modified from a set of four pre-defined experiments to a set of three experiments that provided increasing independence. In the third and final experiment, students conducted their own background research, proposed experiments, built apparatuses, and tested their hypotheses.

In general, the changes reflected a transition in the course from passive learning to active learning [2, 9]. Rather than having students passively absorb knowledge and reproduce it by following a step-by-step procedure, the course redesign had them actively pursue experimental knowledge. In the first nine weeks of the course, students were gradually trained to become independent experimenters. In the last four weeks, they actively designed and conducted an experiment of their choosing. This project-based learning approach had students combine the knowledge they already had with additional knowledge they gained in developing their own experiments [10]. Students completed all of these tasks in teams, further facilitating this project-based education [11]. Incorporating project-based education into a course where it was previously absent is in line with the leaders at the forefront of engineering education [12]. In this revised structure, students not only learned experimental technique, they also learned to identify and formulate their own problems and solutions.

Course Modifications

The broad goal of the modification discussed in this paper was to shift the focus of the junior mechanical engineering laboratory course from following fully pre-planned experiments to experimental design. The efficacy of the changes were tracked with matched pre- and post-surveys.

Prior Course Structure

In its previous iteration, the course began with five weeks of relatively traditional in-class instruction to teach students probability, statistics, and lab safety. That five-week period was then followed by four two-week lab sessions that were conducted in four-to-five person teams. Within these lab sessions, there were four unique experiments occurring simultaneously, with a team on each. After two weeks, the teams rotated. The prior structure is shown in Table 1. For each experiment, students were given source materials and a detailed set of instructions that walked them through, step-by-step, how to complete the lab. After each experiment, the students submitted lengthy reports where they detailed their methodology and analysis. These reports relied heavily on the statistical techniques learned during the initial five-week instructional period.

Table 1: Mechanical engineering laboratory I, current course structure:

Weeks	**Content Description**
1-5	Probability, statistics, lab safety instruction
6-7	Experiment 1
8-9	Experiment 2
10-11	Experiment 3
12-13	Experiment 4

The course used sophisticated apparatuses to have students explore fundamental fields within mechanical engineering. These fields included fluids, heat transfer, thermodynamics, and material properties. The lengthy experiments succeed in exposing students to a variety of fields within mechanical engineering and a variety of analytical tools.

Since the apparatuses used in that course format were relatively complex, the existing instructions were very detailed (e.g. one experiment had students perform a detailed image analysis of points on a piece of metal as it is stretched to assess how different regions deform). While these instructions ensured students were able to correctly conduct the experiment, they had negative consequences. Students did not get to make choices about which equipment/sensors to use to reach an experimental goal. Second, many of the existing labs did not have engaging roles for all four to five students on a team. Often, one or two students took the lead while the rest watched. Third, since the guidelines were rigidly spelled out within each experiment, students did not get the chance to do background research to find a mechanical engineering problem of their own. Similarly, students did not get a chance to synthesize that background research and use it to formulate their own hypothesis. They in turn did not have a choice in which data they collected or which statistical techniques they used to analyze that data and test their own hypothesis. Finally, in order to meet all of the requirements in the existing experiments, the lab reports that students wrote were too long and time-consuming. Students did not get practice stating their thoughts clearly and succinctly, and instead, simply included content to meet every requirement in the detailed rubrics they were given. Due to the length, it was difficult for course assistants to give detailed feedback on their writing, and as a result, students' writing skills stagnated.

New Course Structure

In an effort to address these shortcomings, scaffolded experimental design was incorporated into the course. The first five weeks of the course maintained their current structure, as course reviews and informal discussions with students had indicated their effectiveness. The eight weeks of experiments in the prior structure were replaced by modules that guided students towards the creation of independent experiments (Table 2).

Table 2: Mechanical engineering laboratory I, proposed course structure:

Weeks	**Content Description**
1-5	Probability, statistics, lab safety instruction
6-7	Fully-guided experiment
8-9	Partially-guided experiment
10	Students do background research and propose a new experiment
11-13	Students design and conduct their new experiments
14	Students present their findings and submit final conference-style papers

Weeks 6-7: Fully-guided Experiment

In weeks 6-7, during the fully-guided experiment, students were formed into randomized two-person teams. Students performed a fully-guided experiment in which they approached the same experimental goal using the same sensors, but they had to decide how to take in data and what to do with it. The experiment had students assess whether blowing on a hot drink increases the cooling rate. Instructions were given to students in the form of a conference-style report (i.e. double-column, six-page maximum). This report had the Introduction and Methods sections completed, with the Results and Discussion sections partially completed. Students followed along with the Methods section as they attached a temperature sensor to an insulated cup and to an Arduino microcontroller for data collection. They also constructed a stand with a small fan on it to simulate the “blowing on a hot drink" condition (Figure 1).

Students chose how many samples to collect and at what interval they should collect those samples. They then chose how to use the statistical and uncertainty techniques taught during the first five weeks of the course to compare the two conditions. Students completed their data analysis in Matlab. Assessment was completed by having students finish the partially completed sections of the report in LaTeX to show whether there was a statistical difference between the two cases. Students were also asked in this report to critically discuss the shortcomings of the experimental setup. As the written portion was considerably shorter than in the prior form of the course, teaching assistants were able to give more meaningful writing feedback.

The goal of the fully-guided experiment was to introduce students to the concept of creating an experimental setup and to familiarize them with data acquisition using an Arduino.

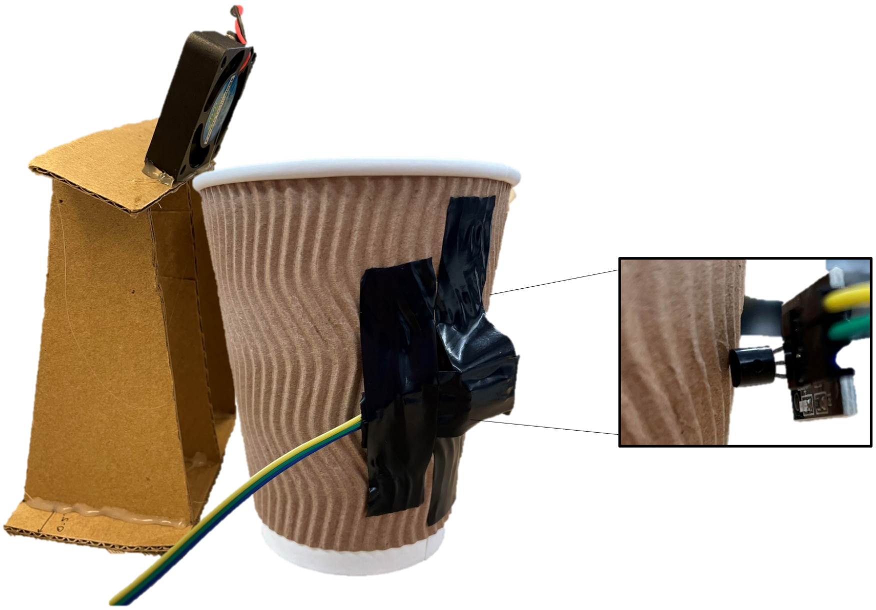

Figure 1: The experimental setup for the “blowing on a hot drink" condition in the fully-guided experiment. The fan sits atop a student-constructed stand pointing at the hot drink. A zoom in of an 18B20 temperature sensor attached to the outside of the cup is shown. The temperature data from this sensor is collected by an Arduino microcontroller.

Weeks 8-9: Partially-guided Experiment

In weeks 8-9, during the partially-guided experiment, students were first reformed into new randomized two-person teams. Here students approached the same experimental goal, but they had to choose which sensors to use to reach that goal. Additionally, they had to build the apparatus needed to use those sensors, they had to made the decision about which the data they took, and had to decide themselves how to analyze it. The experiment had students analyze whether 6061 aluminum and acrylic had the same modulus of elasticity. The motivation for the experiment, and the basic theory underlying how to obtain the modulus of elasticity from measuring the free vibration of a beam, were given to students in the form of a conference-style report with the Introduction and a part of the Methods sections completed. Students then had to choose sensors from the ELEGOO 37 in 1 Sensor Modules Kit (Figure 2) to measure that free vibration.

The goal with the partially-guided experiment was to increase student independence from the fully-guided experiment. Students gained experience with making open-ended sensor and experimental apparatus choices. In their analyses, they had to carefully think through the consequences of those choices. Different sensors had different capabilities for making the rapid time-varying measurements that students were tasked with taking. Students chose a variety of techniques for measuring the vibration. The most common choice was the ultrasonic sensor. Many other sensors were also used though, including the laser emitter coupled with the photo resistor and a magnet coupled with a linear hall effect sensor (Figure 3). Each sensor choice had unique uncertainty analysis that had to be applied with it. The experiment marked a significant

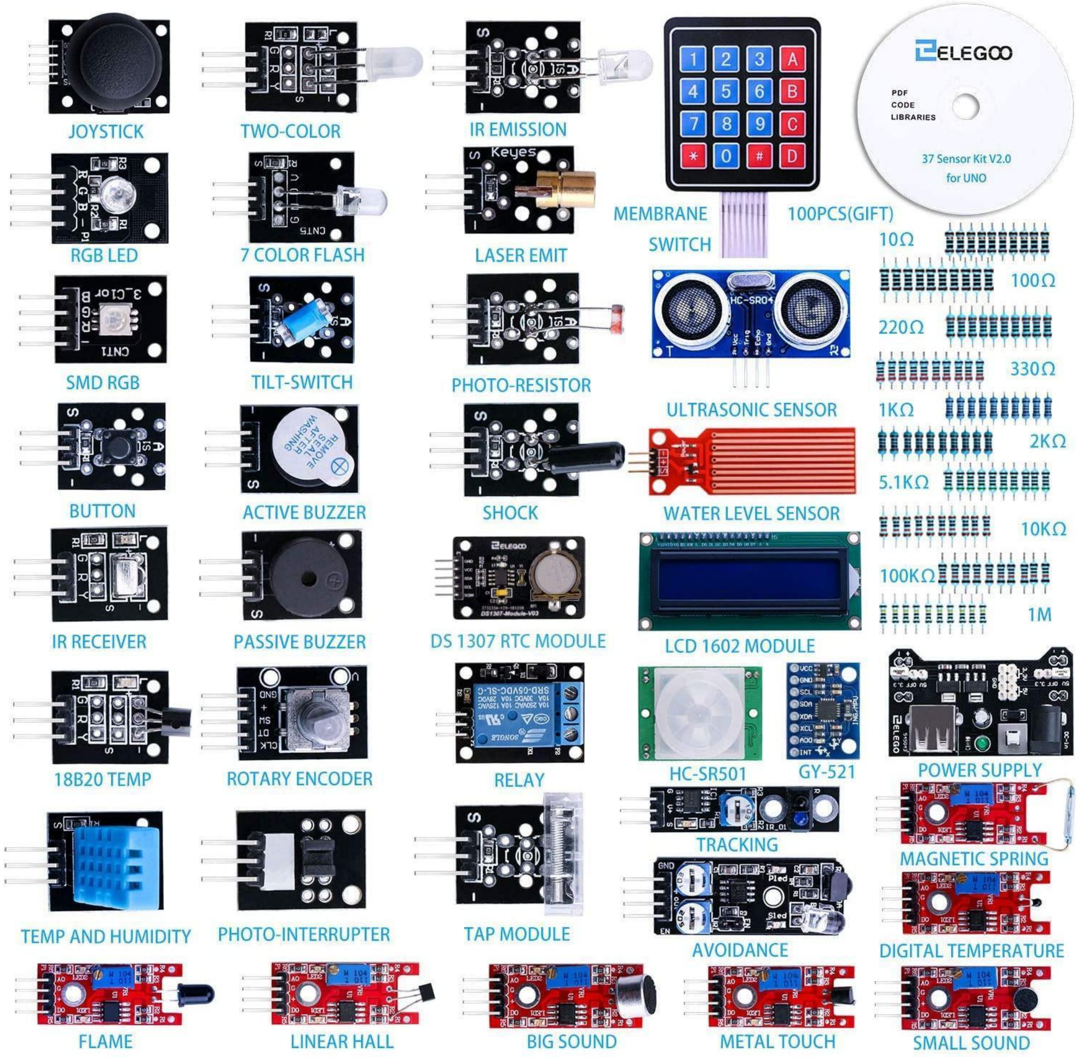

Figure 2: The sensors in the ELEGOO 37 in 1 Sensor Modules Kit [13] that students could choose to measure the free vibration of the beams of alumninum and acrylic.

jump in open-ended complexity from the fully-guided experiment. As before, assessment was completed by having students finish the partially completed report with their Methods, Results, and Discussion.

Weeks 10-13: Novel Experiments

During week 10, students transitioned towards designing their own experiments. They began by reforming into two-person teams of their choosing. They then identified a mechanical engineering problem, conducted background research, and proposed a hypothesis. Students then submitted an experimental proposal where they outlined the problem, hypothesis, and a plan to construct the experimental apparatus needed to test the hypothesis. During the following three weeks, students constructed their apparatuses, conducted their experiments, and used statistical techniques to analyze their results. Throughout these three weeks, students developed their conference-style lab reports. These were done iteratively, with outlines of different report sections submitted as the

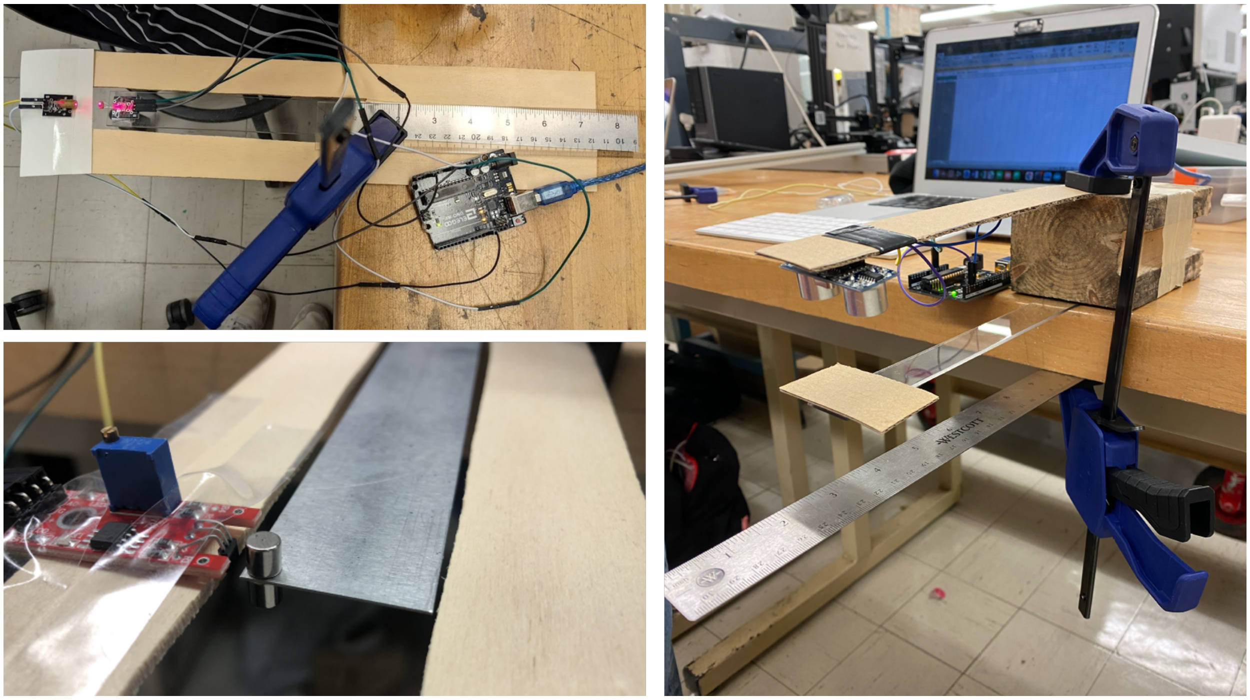

Figure 3: Three examples of student apparatuses for measuring the free vibration of acrylic and aluminum beams. The top-left image shows a photo resistor and a laser emitter setup. Bottom-left shows a magnet with a hall effect sensor. Right shows an ultrasonic sensor.

experiment went on. During the last class, students presented their methodology and findings in a short class presentation. In making these presentations short, the emphasis was on clear and succinct communication.

Students pursued a wide variety of experiments in this portion of the course (Figure 4). These projects spanned the mechanical engineer disciplines. Anecdotally speaking, students showed great passion in completing these projects, as they were pursuing problems that interested them.

Assessment

The course modifications described above were run for two cohorts of mechanical engineering students. In Fall 2020, 60 students participated in the class. During this semester, the course took place entirely online due to the COVID-19 pandemic. Students were sent kits to their homes to complete the experiments. Students received an Arduino microcontroller, the ELEGOO 37 in 1 Sensor Modules Kit [13], and a variety of basic construction materials to create apparatuses. In Fall 2021, an additional 79 students participated in the class. During this semester, the course took place entirely in-person. Students had access to the same materials as the previous year, however, they also had access to the entire machine shop space, which meant they could build more sophisticated apparatuses than the previous year.

In order to assess the effectiveness of the changes on the course, pre- and post-surveys were

Figure 4: Six examples of student self-created experiments. Top-left shows an experimental setup for measuring the speed of sound as a function of humidity. Top-middle shows a calorimetry setup designed to measure the specific heat of nickels in order to determine their material properties. Top-right shows a setup for measuring the effectiveness of different geometries on acoustical attenuation. Bottom-left shows an experimental setup for measuring droplet size and travel speed in various humidity conditions. Bottom-middle is an experiment measuring the effectiveness of different turbine geometries. Bottom-right shows an experimental setup for measuring stress and strain of fabric samples.

given. The pre-survey was given after the more traditional instruction in the first five weeks, but prior to the beginning of any experimentation (Table 2). The post-survey was given after the completion of the student self-designed experiments, just prior to their final presentations. The quantitative portion of these surveys assessed three areas using a Likert scale. In the first area, the surveys assessed student perception of their skill-level in key course goals (topics shown in Table 3). In the second area, they assessed student perception of their progress in the course learning goals (goals shown in Table 4). Lastly, since one of the overarching goals of undergraduate education is to prepare students for future endeavors, we also sought to assess their gains in lifelong learning ability (question set shown in Table 5). Studies exploring lifelong learning ability are well established [14, 15, 16], and were used for similar assessments here. Pre- and post-surveys were matched for both cohorts, totaling to 79 matched responses (of the 139 total students that took the class, 24 matched pairs were obtained from the Fall 2020 cohort and 55 matched pairs were obtained for the Fall 2021 cohort). Each topic within the three areas was assessed for significance using paired t-tests.

In addition to the quantitative questions above, one qualitative open-ended question was asked:

You have been tasked with experimentally answering a mechanical engineering question. Some example questions are shown below. These are exemplary in nature and are not meant to be all inclusive. In a numbered list below, describe your step-by-step process to experimentally answer a mechanical engineering question similar to the ones below. Did two screws come from the same manufacturing plant? What is the natural frequency of vibration of a given cantilever beam? At what rate does water cool from boiling to room temperature?

For this question, in the Fall 2020 cohort, an emergent analysis was conducted [17] on the 73 total pre and post responses. The research team read a subset of the pre- and post-survey responses (10 responses from each survey) to the question above and identified themes and patterns in student thinking. A research team member developed initial code definitions based on those themes and then refined those definitions based on feedback from the team and results of an initial round of coding the full set of responses, with two coders assigned to each response (codes and examples can be seen in Table 6). A further analysis was then conducted for the set of 24 paired responses on each of the themes. At the time of writing, this analysis had yet to be conducted for the Fall 2021 cohort.

Results

Student perception of their skill levels in key course goals showed a marked improvement across all categories (Table 3). Significance at the 99% confidence level was observed for all categories aside from oral presentation (significant at the 90% confidence level with $p = 0.07$). The largest improvements were observed in prototyping and designing.

Table 3: Student perception of their skill levels in key course goals (N=79)

Rating Category	Mean Difference	t	P-Value
Idea Generation	0.41	3.83	<0.01
Designing	0.61	6.12	<0.01
Prototyping	0.71	6.37	<0.01
Oral Presentation	0.18	1.83	>0.05
Teamwork	0.25	2.78	<0.01
Problem Solving	0.33	4.22	<0.01
Confidence	0.33	3.10	<0.01
Ability to adapt to new situations	0.39	3.71	<0.01

Similar improvements were seen in the course learning objectives across all categories (Table 4). Significance at the 99% confidence level was observed for all categories. The largest improvements came in student ability to write conference-style lab reports, ability to design/build experimental apparatuses, ability to develop techniques for experimentally testing a hypothesis, and the ability to visualize experiments that test fundamental mechanical engineering concepts.

The results for the lifelong learning question set did not follow a similar trend to the previous two question sets (Table 5). Significance at the 99% confidence level was only observed for 3 of the 14 categories. Students showed significant improvement in their ability impose meaning upon

Table 4: Results of the learning objectives question set (N=79).

Learning Objectives Question	Mean Difference	t	P-Value
I am able to utilize probability basics and sophisticated statistical techniques to assess uncertainty in laboratory experiments.	0.84	6.66	<0.01
I am able to utilize and characterize a variety of lab apparatuses to measure and test mechanical engineering hypotheses.	1.05	7.94	<0.01
I am able to understand and use computational techniques (e.g. software such as MATLAB, ANOVA, Labview etc.) to visualize and characterize data.	0.77	7.47	<0.01
I have a fundamental understanding of the types of transducers that underlie modern sensors.	0.94	8.29	<0.01
I am able to visualize lab experiments that test fundamental mechanical engineering concepts including stress-strain analysis, heat-transfer, and material properties.	1.35	11.20	<0.01
I am able to participate in lab experiments that test fundamental mechanical engineering concepts including stress-strain analysis, heat-transfer, and material properties.	1.16	7.44	<0.01
I am able to identify/formulate a mechanical engineering problem that requires experimental testing/validation.	1.22	9.29	<0.01
I am able to conduct background research on the problem in order to form a testable hypothesis.	0.92	-7.50	<0.01
I am able to develop the technique for experimentally testing a formulated hypothesis.	1.32	10.95	<0.01
I am able to design and build an experimental apparatus for testing my hypothesis.	1.37	11.97	<0.01
I am able to use statistical techniques to develop conclusions on that hypothesis.	1.13	8.81	<0.01
I am able to create a conference-style lab report that succinctly and clearly summarizes my background research, methodology, results, discussion of the results, and experimental conclusions.	1.53	10.81	<0.01
I am able to synthesize and present my methodology and results in a short presentation.	0.87	-7.83	<0.01

what others see as disorder, their ability to relate academic learning to practical issues, and their ability to deal with the unexpected. Though it is not shown in the table, the “I feel others are in a better position than I am to evaluate my success as a student" decrease was significant at the 90%

confidence level ($p = 0.06$).

The other lifelong learning questions generally showed slight improvement (defined as positive for positively worded questions and negative for negatively worded questions), or, no trend. For example, for the “I prefer problems for which there is only one solution" prompt, the mean difference was negative, indicating a preference for more open-ended problems, but without significance ($p = 0.23$). Both the “it is my responsibility to make sense of what I learn at school" and the “I love learning for its own sake" prompts showed no change.

Table 5: Results of the lifelong learning question set (N=79).

Lifelong Learning Question	Mean Difference	t	P-Value
I am able to impose meaning upon what others see as disorder	0.48	5.35	<0.01
I try to relate academic learning to practical issues	0.28	3.65	<0.01
When I approach new material, I try to relate it to what I already know	0.09	1.09	>0.05
I prefer problems for which there is only one solution	-0.13	-1.22	>0.05
I can deal with the unexpected and solve problems as they arise	0.25	2.90	<0.01
I feel uncomfortable under conditions of uncertainty	0.03	0.17	>0.05
I feel others are in a better position than I am to evaluate my success as a student	-0.24	-1.90	>0.05
It is my responsibility to make sense of what I learn at school	0.00	0.00	>0.05
I prefer to have others plan my learning	0.01	0.12	>0.05
I seldom think about my own learning and how to improve it	-0.09	-0.70	>0.05
I feel I am a self-directed learner	0.09	0.77	>0.05
I love learning for its own sake	0.00	0.00	>0.05
When I learn something new I try to focus on the details rather than on the ‘big picture’	-0.08	0.69	>0.05
I often find it difficult to locate information when I need it	-0.13	1.09	>0.05

Table 6 shows the percentage of student responses in the pre- and post-surveys to which each code was applied for the qualitative responses. An example for each code is also shown. There are large increases in the percent of students framing their approaches around hypotheses and discussing background research, experimental design, statistical analysis, uncertainty analysis, interpretation of results, and communication of results. Far fewer students expressed uncertainty about how to approach an experimental question in mechanical engineering on the post-survey than on the pre-survey, and in fact the one response coded as Unsure/Blank on the post-survey was blank. Students were more likely to phrase their responses in first person on the pre-survey and in second person on the post-survey.

We further investigated these changes by considering those responses from students who answered both surveys. Table 7 shows the number of these responses that were categorized in a given code for both the pre- and post-surveys, the pre-survey only, and the post-survey only. The matched code counts largely confirm the conclusions from the full set of responses. They do, however, give additional insight into some codes where we see little overall change. For instance, a quarter of the students in this sample mentioned taking multiple samples only on the post-survey, but we see minimal change here because nearly the same number of students failed to mention this on the post-survey after including it in their response on the pre-survey. The same is true for students framing their responses around a problem or solution.

Within the matched responses, we studied relationships among changes from the pre-survey to the post-survey. Interrelated changes that stood out include:

- Those students who expressed uncertainty about how to proceed on the pre-survey almost all included background research in their post-survey procedure.
- Students who included background research or a hypothesis framing in their post-survey procedure after not doing so on the pre-survey were also likely to newly include the other.
- For students who included experimental design, statistical analysis and uncertainty analysis, and communication of results and interpretation of results similarly fed into each other.
- Newly framing the procedure around a hypothesis on the post-survey often led students to mention interpreting results for the first time as well, and including interpretation of results led students to discuss background knowledge or research.
- Students who discussed doing multiple trials on the post-survey after not doing so on the pre-survey also tend to include statistical analysis in their procedure on the post-survey.
- Students newly writing in the imperative on the post-survey all wrote in first person on the pre-survey, and vice versa. Responses in second person on the post-survey came from students who wrote in either the imperative or first person on the pre-survey.

Table 6: Percentage of student responses to which each code was applied for the Fall 2020 cohort (N = 73, 35 Pre-Survey, 38 Post-Survey)

Code	Pre-Survey %	Post-Survey %	Examples
Background Research	31%	66%	"Write all relevant equations/information to help know what phenomena are occurring"
Hypothesis Framing	29%	58%	"You can perform hypothesis testing, such as a two tail t test to see if we reject the null hypothesis."
Solution/Problem Framing	40%	39%	"1) identify the problem. 2) determine what (...) is needed to solve problem"
Experimental Design	34%	76%	"Choose an experimental apparatus that limits confounding factors"
Statistical Analysis	20%	53%	"Perform statistical analysis to see if data confirms/rejects null hypothesis."
Uncertainty Analysis	9%	24%	"Calculate uncertainties due to constraints or approximations that were made during the experiment."
Interpretation of Results	14%	45%	"Discuss the findings from this statistical analysis and try to make sense of it using the details of your experiment"
Communication of Results	9%	24%	"Write report"
Multiple Samples	23%	32%	"Perform the experiment with sufficient trials to gather data that is signicant enough to perform analysis on"
Person: None, Imperative	49%	45%	"Look at results, run some calculations to see standard deviation, average and etc"
Person: First	46%	21%	"1- I read the question. 2- I think of any type of anecdotal evidence I have directly relating to the question."
Person: Second	0%	16%	"Measure mean and standard deviation of what you are trying to measure"
Person: Mixed First/Second	0%	5%	"1.) You can perform hypothesis testing, such as a two tail t test to see if we reject the null hypothesis that the two values are similar."
Person: None, Non-Imperative	0%	11%	"1- question. 2-background info"
Example Only	11%	11%	"Taking the example of determining if two screws come from the same plant"
Unsure/Blank	23%	3%	"I honestly have no idea."

Table 7: Paired student responses to which each code was applied for the Fall 2020 cohort (N=24)

Code	Both Surveys	Pre-Survey Only	Post-Survey Only
Background Research	7	1	7
Hypothesis Framing	5	2	9
Solution/Problem Framing	4	6	4
Experimental Design	9	1	10
Statistical Analysis	5	2	7
Uncertainty Analysis	2	1	5
Interpretation of Results	2	2	8
Communication of Results	1	1	6
Multiple Samples	2	5	6
Person: None, Imperative	4	6	5
Person: First	5	8	2
Person: Second	0	0	4
Person: Mixed First/Second	0	0	1
Person: None, Non-Imperative	0	0	2
Example Only	1	2	1
Unsure/Blank	1	4	0

Discussion

Overall, the course modifications introduced into the junior-level laboratory course led to large improvements in student learning. The improvement across student perception of their skill levels in key course goals as well as on the course learning objectives showcases that the redesign was successful. Students displayed increased mastery across the topics that the course was intended to teach. Increases in their ability to confidently solve problems using experimental design track favorably with their increased ability to create hypotheses and conduct experiments.

The only topic in these first two question sets that did not achieve a significant improvement at the 99% confidence level or greater was the oral presentation course goal. The lack of significance at this level may be due to the timing of the post-survey. Due to time constraints, the post-survey was given just prior to students' final oral presentations. The small improvement in this key goal indicates that prepping for the final presentation led to some increase in presentation ability, but perhaps measuring it after the presentation would give a clearer indication of students' perceived improvement.

The lifelong learning question set paints a less clear picture. The significant improvements in student ability to impose meaning upon what others see as disorder, ability to relate academic learning to practical issues, and ability to deal with the unexpected show promise that the course will have an impact long after students have taken it. Still, the lack of significant improvement in the majority of the categories points to room for future course improvement. One way to improve these metrics would be to more deliberately discuss their relationship to the course. For example, pausing to have students reflect on the myriad of possible solutions to their self-designed experiments could lead to a more deliberate emphasis on the "I prefer problems for which there is only one solution" lifelong learning prompt. For other prompts, additions to the course might prove impactful. For the "I feel others are in a better position than I am to evaluate my success as a student" prompt, adding in a self-reflection and/or self-grading component to the course might allow students to more critically evaluate themselves and their learning.

The responses to the open-ended qualititative prompt also proved insightful. Students produced far more detailed procedures for approaching experimental questions in mechanical engineering, even apart from a specific context, after the redesigned course than they did before the course. Their procedures were also more complete, with a higher percentage of students including each of the components of experimental work in mechanical engineering identified in the course learning objectives. In particular, students were much more likely to address experimental design, statistical analysis, and interpretation of results following the course than they had been before. Students were also more likely to frame their procedure around formulating, testing, and considering evidence for and against a hypothesis. This is opposed to solely solving a question or problem, though this alternate framing persists in parallel to the hypothesis-driven approach that is explicitly encouraged through the learning objectives and course.

There is some shift from before to after the course in the language that students use in their procedures. Overall, this is from first person to second person. However, this movement is not direct; students who used the first person initially wrote in the imperative without personal pronoun use on the post-survey, and some students who initially wrote in the imperative then wrote in second person. The decrease in first person usage may be related to students arriving at a more standardized approach to experimental mechanical engineering questions through the course, removing personal aspects of their pre-survey approach. However, these changes are not strongly related to any other shifts in student procedure, so this is not clear.

These qualitative results, when treated as a measure of student learning, are in line with quantitative analysis from the pre- and post-surveys, which showed that students were far more confident in their abilities in each of the learning objectives following the course than they were before it. Further evidence for this from the qualitative analysis is that, unlike on the pre-survey, on the post-survey no students expressed uncertainty about how to approach experimental questions.

While the results indicate that the course modification was generally a success, there is room for improvement and further exploration in the analysis. As there was a desire to introduce the potentially beneficial course modification as quickly as possible, no similar surveys were conducted for the course in its previous iteration. Therefore, the improvement is not compared against what might have been a similar improvement in the prior form of the course. Anecdotally, students in the new course format expressed much more positive opinions than students in the previous course format, but there is no rigorous data to confirm this. Furthermore, as noted earlier, the Fall 2020 cohort took the course online, while the Fall 2021 cohort took the course in-person. Though students had similar basic kit items in both cases, the Fall 2021 cohort had access to considerably more options on campus. Analysis of the separate cohorts could illuminate the differences in at-home vs in-person learning for a hands-on course. Included within this analysis would be an extension of the emergent coding technique to the Fall 2021 cohort. Demographic analysis could also illuminate whether the course benefits were universal across populations. Lastly, it would be interesting to see the lasting effects of the course. As noted, the surveys were given immediately prior and after the experimental portion of the class. Giving the surveys again after a year or longer could illuminate whether the positive effects were temporary or lasting.

Still, despite the shortcomings and room for future analysis, overall, these results suggest that the redesigned course was effective in introducing students to the key components of the experimental process in mechanical engineering. They show the promise of scaffolded design-based learning in teaching students to handle open-ended problem explorations.

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