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A Low-cost Materials Laboratory Sequence for Remote Instruction that Supports Student Agency

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Abstract

Under the new ABET accreditation framework, students are expected to demonstrate “an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions” [1]. Traditional, recipe-based labs provide few opportunities for students to engage in realistic experimental design, and recent research has cast doubt on their pedagogical benefit [2]. At the same time, the COVID-19 pandemic has forced institutions to move to remote learning.

To address these challenges we developed a series of online labs for an upper-division mechanics of materials course. The first three labs consist of video demonstrations of traditional lab experiments with synchronous group discussions and data analysis. Two of these “traditional” virtual labs are supplemented with peer-teaching video activities. The final lab is a guided-inquiry activity focused on experimental design. Using only materials available at home, students measure the Young’s modulus of aluminum and use their results to design a hypothetical product. In order to provide the same opportunity for students around the world, the test specimen is taken from an aluminum beverage can.

One measure of whether or not an activity supports student agency is the diversity of solutions generated by students [3]. We analyzed 36 reports from the final guided-inquiry lab and coded the experimental procedure on five key decisions such as the type of experiment performed, specimen geometry, and measurement method. We identified 29 unique approaches to the problem, with no one approach accounting for more than three submissions.

Student outcomes were measured by a survey of students’ attitudes and self-efficacy administered directly after every lab activity except for the first one. The fraction of students endorsing statements related to a sense of agency increased dramatically between the “traditional” labs and the guided-inquiry lab: from 52% to 82% for goal-setting and from about 64% to 92% for choice of methods. Self-efficacy increased significantly in the primary targeted skills (designing experiments, making predictions, and generating further questions), but there was no significant shift in skills not explicitly targeted by the guided-inquiry lab (equitable sharing of labor, expressing opinions in a group, and interpreting graphs).

Our experience demonstrates that at-home lab activities can achieve sophisticated learning outcomes without the use of lab equipment or customized kits.

Introduction

The instructional laboratory experience is a hallmark of the modern engineering curriculum. Engineering students typically encounter a variety of lab experiences in different contexts, often designed with different outcomes in mind including reinforcement of lecture concepts, motivation to continue in or pursue a particular major, and development of skills in instrumentation, data analysis, teamwork, and communication [4, 5]. Feisel et. al. emphasized the importance of experimental design, creativity, and learning from failure [4]. More recently, the new ABET accreditation framework requires that students demonstrate "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions" [1].

In mechanical engineering, civil engineering, and materials science, some of these lab experiences invariably involve material testing, and usually use the relevant ASTM standard as a template. A traditional "recipe-based" lab guides students through a standardized experiment using well-documented methods leading to predictable results. The activities that students may engage in during the activity are heavily constrained by the available equipment, safety considerations, and time. Similar lab activities in introductory physics have proven ineffective at reinforcing lecture concepts, and the limits on student agency preclude achievement of the objectives emphasized by ABET [2, 6].

One approach to creating more authentic lab experiences is to simplify or remove the instructions such that students must exercise some judgement to complete the activity [7]. This approach has shown mixed results in engineering contexts [8, 9, 10], though more research using specific and valid assessment instruments is needed. Another approach is to design a sequence of lab activities with decreasing support and increasing room for student agency. Students engaged in open-ended lab activities learn more, make more expert-like decisions, and develop more sophisticated attitudes about experimental science. [11, 12].

The rapid shift to remote instruction in Spring 2020 in response to the COVID-19 pandemic had a particularly powerful impact on laboratory activities. Instructors moved their classes online using a variety of methods, including mailing physical kits, designing simulation-based exercises, and providing experimental data. Many group-based activities were converted into individual projects and students reported difficulties getting guidance and support [13]. Some instructors responded by designing guided inquiry activities which could be completed at home, either with widely-available household supplies or mailed kits [14, 15]. Kits can be expensive and resource-intensive to assemble, and may encounter difficulties in transit.

Here we report on a low-cost, scaffolded laboratory activity sequence culminating in an experimental design activity in which each student team develops and conducts their own experiment to measure the Young's modulus of the aluminum in a beverage can.

Table 1: Comparison of lab activities in Fall 2019 (in-person) and Fall 2020 (remote).

Topic	Fall 2019	Fall 2020
Combined loading	Lab 1 (in-person)	
Heat Treatment of Metals	Lab 2 (in-person)	Lab 1 (virtual)
Uniaxial Tension Testing	Lab 3 (in-person)	Lab 2 (virtual) Peer-teaching video: sample design, instrumentation, and validity criteria
Fracture Toughness Testing	Lab 4 (in-person)	Lab 3 (virtual) Peer-teaching video: qualitative fracture surface analysis
Experiment design		Lab 4: Guided-inquiry design challenge

Scaffolded lab sequence

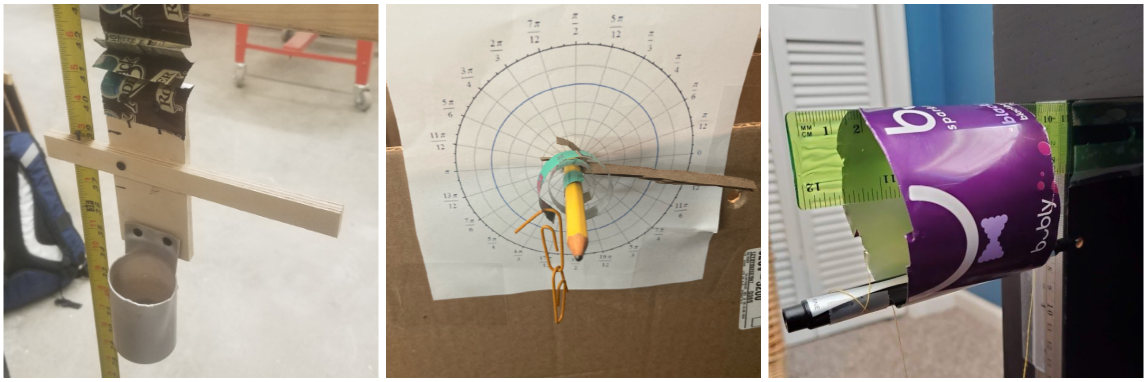
Course details

This study took place in the context of a junior-level mechanics of engineering materials course at Cornell University with a total enrollment of 132 students (three students dropped the course, and two students opted out of data collection). In previous years, the course included four traditional in-person lab activities conducted in groups of 2-3 students in sections of 10-15 students. All lecture and lab section meetings were held as synchronous virtual meetings. Recordings were captioned and made available to students later the same day. Some recitation sections met in-person while others met virtually. 95% of students were located in the same time zone as the institution or within 3 hours. This study was approved by the Cornell University Institutional Review Board under protocol #1708007347.

The lab activities are shown in Table 1. One of the in-person labs (combined loading) was discarded entirely. The heat treatment, uniaxial tension testing, and fracture toughness testing labs were modified for the virtual format and supplemented with peer-teaching video assignments, and a new experimental design lab was added.

Virtual "traditional" labs

We redesigned three of the existing lab activities for the remote instruction format. Students first watched a 15–20 minute pre-recorded video with a brief introduction to the lab by the instructor followed by a demonstration of the equipment and experiment with voiceover narration. Before their assigned lab session meeting, students completed a pre-lab quiz to familiarize themselves with the relevant ASTM standard and to make qualitative and quantitative predictions about the outcomes of the test. During the (online synchronous) lab meeting, lab teams met separately (using Zoom breakout rooms) to talk about a series of discussion questions, then participated in a whole-class discussion, and asked questions about the lab analysis tasks. Students were given a report template for each lab to provide a standard format and to give examples of good writing practices. Each successive template included less pre-written content.



(a) (b) (c)

Figure 1: Three examples of student-designed experiments for Lab 4: **(a)** Folded "accordion spring" design. **(b)** Torsional spring. **(c)** Diametral tension test.

Peer-teaching video activities

Alongside the second and third lab activities, students were asked to create and share 5-minute videos about mechanical testing. For the second lab, students recorded a low-fidelity demonstration of the uniaxial tension test with household materials, describing the important aspects of specimen design, instrumentation, and validity criteria. For the third lab, students chose two materials to perform a three-point bending fracture "test" on and compared the morphology of the fracture surfaces. Students chose whimsical materials like cheese and chocolate for their comparisons. The purpose of the peer-teaching videos was to give students latitude to make independent decisions about testing and gain experience building test fixtures with household materials, but without collecting quantitative data.

Experimental design lab

In the final lab activity, students were asked to measure the Young's modulus of the material in an aluminum can. The activity was presented as a real-world challenge: teams were asked to evaluate the suitability of a "material sample" (an aluminum beverage can) sent by a prospective supplier and finalize the design of a structural boom for a space-based robotic arm to be made of the candidate material. Students were allowed to assume known values for the density and Poisson's ratio, if needed for their calculations. All members of the instructional staff designed and performed their own experiments at home and discussed results and challenges.

Students were given written guidance describing the difference between material stiffness and structural stiffness, using a comparison between a uniaxial tension coupon and a three-point bending specimen as an example. Students were also given information about three example experiments by student teams from Summer 2020 who solved a different but related problem (measuring the Young's modulus of steel wire). The examples included two static deflection experiments (cantilever beam and helical spring) and one dynamic experiment (torsional pendulum).

Students were given a list of 14 guidance questions (given in the appendix) to consider when

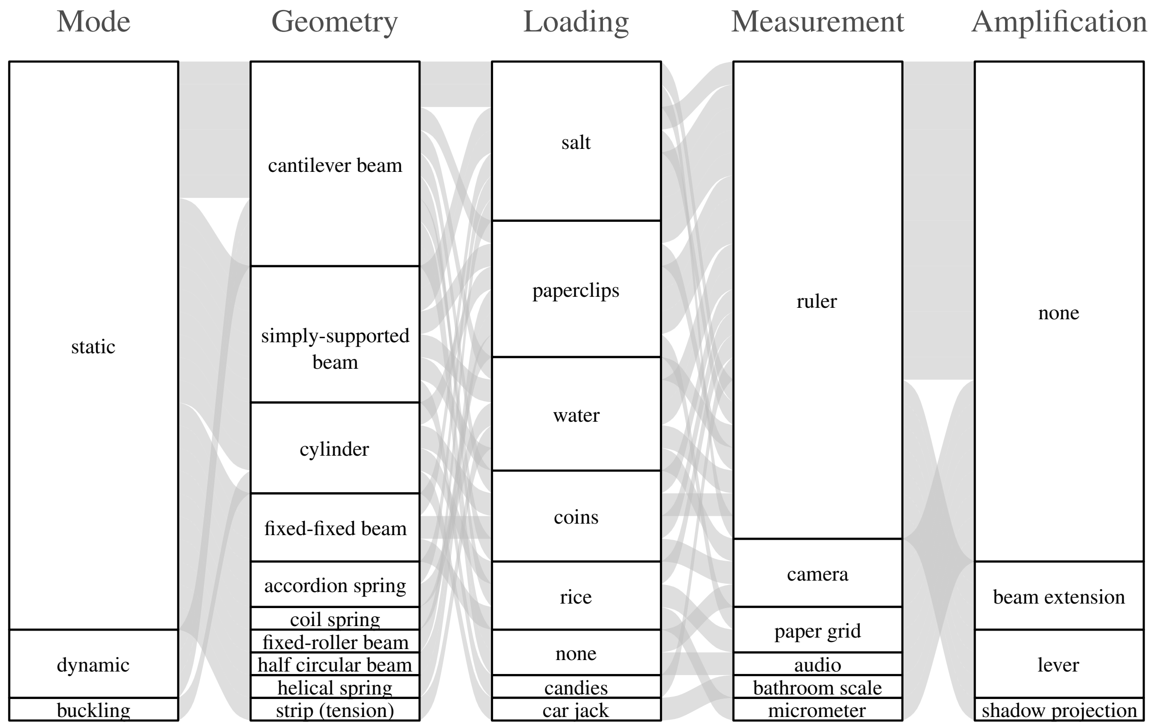


Figure 2: Visual illustration of unique solutions showing distribution of choices at each critical decision.

developing their experiment proposals. Each team brainstormed three initial ideas and then narrowed them down to one concrete proposal, which was then reviewed by instructional staff in meetings with each team. Staff were instructed to use the guidance questions to structure their feedback and to refrain from suggesting specific solutions not considered by the students themselves. Additional office hours specifically for help with the lab were scheduled at times convenient for local and overseas time zones.

Three examples of experiments designed by students are shown in Fig. 1.

Solution diversity analysis

A genuine and successful guided-inquiry activity should not only shift important decisions onto the students, but the goal itself should reasonably afford multiple successful approaches. Willner-Giwerc et. al. [3] proposed *solution diversity* as one measure of the success of a guided-inquiry activity. A large number of unique (successful) solutions is evidence that the activity is truly open-ended and that students are engaging in genuine problem-solving and decision-making. A small number of unique solutions is evidence that either there are too many constraints on the problem, or that students lack the tools to make independent decisions.

We examined the procedure section of all 42 lab reports and coded the choices made by the team across a set of five decisions: the mode of the test (static deflection, dynamic, or buckling), the specimen geometry (e.g. cantilever beam, cylinder), the loading method (e.g. paperclips, hydraulic car jack), the measurement tool (e.g. ruler, video camera), and amplification method (e.g. lever, shadow projection). Six reports were excluded from analysis due to incomplete information. Many minor decisions which were crucial to the success of the experiment, such as the method of sample preparation or orientation of the specimen along the can, were not coded.

The space of solutions is presented graphically in Fig. 2, where the height of each choice is proportional to the number of teams that selected it. We define a "solution" as the set of five specific choices made by the team, e.g. static deflection test, cantilever beam, loaded with coins, measured by ruler, no amplification. Each path through Fig. 2 represents a unique solution. Out of 36 reports with complete data, the class generated a total of 29 unique solutions, with no one solution being shared by more than three reports. Even if the loading method is coded more generally (e.g. "hung deadweight" or "struck at tip"), there are 24 unique solutions, with no one solution being shared by more than four reports.

The solution diversity is apparent not just across reports, but also within each decision category. For example, 31 teams conducted static deflection tests (the most straightforward choice, and also most consistent with familiar mechanical tests studied in the class), but six teams measured resonant frequency of a structure, and one team even conducted a buckling load test. More telling is the surprising variation in sample geometry. The examples of previous experiments on steel wire shown to students included a cantilever beam, a torsional pendulum, and a helical spring. We observed 10 distinct sample geometries (including boundary conditions) ranging from no modification to the can at all, to intricate folded accordion springs from longitudinally-cut strips.

Student agency and self-efficacy

Student attitudes were measured with a brief online survey taken shortly after submitting the tensile testing, fracture toughness testing, and experimental design lab reports. The survey included five items about attitudes towards the lab activity, measured on a five-point Likert scale ("strongly disagree" to "strongly agree"), and eight items about self-efficacy on a five-point Likert scale ("not confident" to "very confident"). A complete list of items is given in the appendix.

Out of 132 students, 75 (57%) completed all three surveys. Mean endorsement level for the attitude items and mean confidence level for the self-efficacy items are shown in Fig. 3. Students' feeling of control over goals and analysis increased dramatically between Lab 3 and Lab 4, as expected. The fraction of students endorsing the control of goals and control of analysis items increased from 52% to 82% and from about 64% to 92%, respectively. However, there was no discernible difference for the related item "I have the freedom to create my best work for this activity." Although we did not conduct validation interviews, it's possible that students are interpreting "freedom to create" as the ability to achieve a good grade or create a polished product, not as the latitude to make independent decisions which lead to success. Students also experienced more surprise about the outcomes of Lab 4, compared with Labs 2 and 3.

The survey included two items directly related to the primary learning objectives of the lab sequence (designing experiments and making predictions), three secondary generic objectives

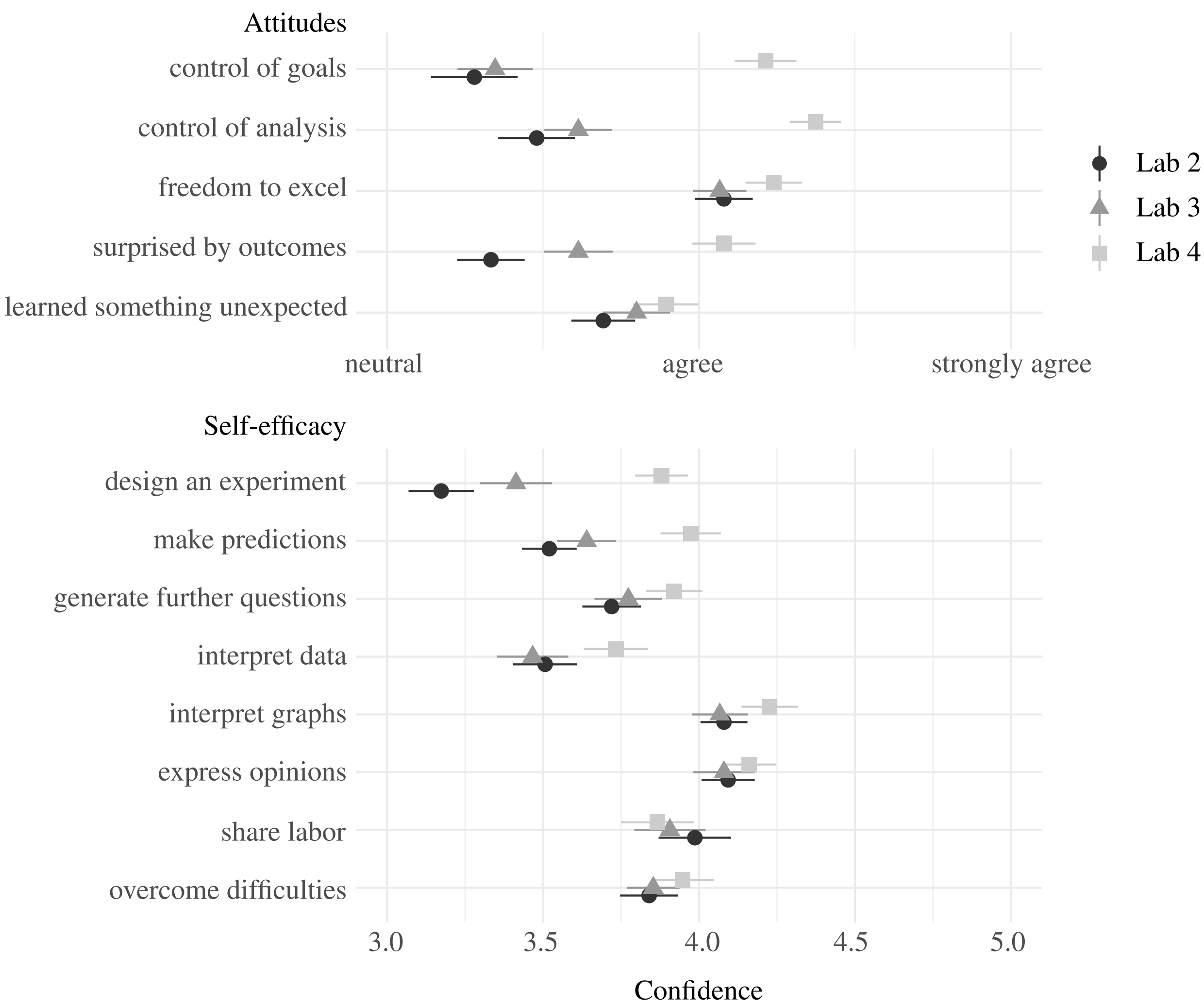


Figure 3: Survey results. Error bars represent $\pm$ 1 standard error.

(generating further questions, interpreting data, and interpreting graphs), as well as three items related to important, but non-targeted skills. Large, significant increases over time were observed for confidence in designing and experiment and making predictions. Contrary to our expectations, we did not observe significant increases in self-reported confidence in the three secondary objectives. The lack of a similar trend in the non-targeted skills suggests that the increase in the targeted skills is due to the lab intervention, and not to differing survey response patterns over time.

Discussion

Although the transition to at-home labs was not made by choice, the new lab sequence affords students the opportunity to practice making and executing design decisions oriented towards a tangible goal. In this regard, it is superior to the type of "cookbook," labs that we used previously when teaching in-person. It also allows us to more meaningfully assess ABET outcome 6: "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions." Our engineering college has developed a series of performance indicators addressing the seven ABET student outcomes which are each assessed periodically in multiple courses throughout the curriculum. Table 2 shows an example rubric for the experimental design lab for the three performance indicators below:

6(a) Develop and execute experimental plan.
6(b) Analyze data and draw conclusions.
6(c) Demonstrate quantitative and engineering judgement.

Table 2: Sample ABET rubric for the experimental design lab.

	Emerging	Progressing	Proficient	Exemplary
6(a)	Multiple details about the procedure are unclear. The boundary conditions do not match the assumptions of the model, or edge effects may dominate. Potential sources of error have not been anticipated.	Experiment could be replicated by another student with clarifications. Boundary conditions are somewhat imprecise, e.g. taped end treated as a pin joint. At least one potential source of error has been identified.	Experiment could be replicated by another engineering student. Boundary conditions are well specified. At least one potential source of error has been identified and mitigated.	Experiment could be easily replicated by another student. Boundary conditions are well-specified and care has been taken to minimize edge effects. At least two potential sources of error have been identified and mitigated.
6(b)	Incorrect relationship between measured stiffness and E. Incorrect or improper analysis technique to relate measurement to model.	Correct relationship between measured stiffness and E based on stated model. Only one data point used to estimate stiffness (e.g. one load increment).	Correct relationship between measured stiffness and E based on stated model. Multiple data points used to estimate stiffness.	Correct relationship between measured stiffness and E based on stated model. Multiple data points used to estimate stiffness *and* uncertainty.
6(c)	Statistical uncertainty not estimated, or estimated incorrectly. Safety factor not justified, or justified in a superficial way.	Estimated statistical uncertainty from relatively unimportant sources of error. Justified safety factor based on 1 of the factors under Exemplary.	Correctly estimated statistical uncertainty from at least 2 important sources of error. Discussed repeatability either between multiple specimens OR experimenters. Justified safety factor based on 2 of the factors under Exemplary.	Correctly estimated statistical uncertainty from more than 2 sources of error. Correctly estimated repeatability between multiple specimens and experimenters. Justified safety factor based on application, uncertainty, and repeatability.

The rubric is written in such a way that it can be meaningfully applied to a wide variety of valid solutions. For example, to demonstrate "exemplary" performance on 6(b), a team could perform a static load-deflection test with multiple load increments and use linear regression to find the slope, or a team could measure the resonant frequency of multiple specimens with different sizes and fit their model parameters to the data.

The activity and rubric were created as a pilot test to see if it was feasible to assess the ABET outcome in this manner, but the performance indicator is not scheduled to be assessed in this course until Fall 2021.

Next, we will discuss some drawbacks to the inquiry-based lab and suggest potential remedies. Although the cost of materials was minimal, the lab sequence required some additional staff time beyond what would have been required for in-person lab activities. The teaching assistants expressed concern that they didn't have enough experience with activities like the experimental design lab to give useful feedback to students. In order to gain experience and anticipate student concerns, the teaching staff brainstormed several possible approaches to the experiment, and then each member conducted their own experiment at home, making sure to choose a variety of experiment types. Afterwards, the first author led a discussion about potential challenges, measurement precision, and practical realization of idealized boundary conditions. This process alleviated the teaching assistants' concerns and helped prepare them to assist students.

Student satisfaction with the labs was mixed: 72% of students rated the value of the laboratory activities as moderately to very valuable, but the majority of free-response comments were either resigned (e.g. "I didn't like having an online lab but I feel like the course staff did the best with what they had to work with.") or negative (e.g. "I did not feel that having us perform the labs at home was helpful for my understanding of the concepts.") Most students feel they missed out on something essential by not being able to operate the test machinery themselves.

How might the benefits of this activity be adapted to in-person instruction to give students a richer and more satisfying experience? First, the final goal—for students to develop an analyze a novel experiment—should remain the same. The only way to teach experimental design is to have students design experiments. Lab facilities could be equipped with more general-use tools, such as calipers and small force gauges, that students could choose to incorporate into their experiment (or not). The design lab could be scaffolded by having students develop and test a portion of the experiment (e.g. design, build, and calibrate their own force sensor) that will be used for their final experiment. Finally, the collaborative element could be enhanced by turning the activity into a competition: e.g. the students wouldn't know the exact form of the specimen until their lab day, during which they would need to use the tools they developed in previous activities to measure the property of interest.

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Appendix

Guidance questions

1. Test specimen design
   (a) How will you make the specimen? Can the method be easily replicated by all your group members?
   (b) What geometric parameters do you need to control and measure?
   (c) How will you calculate the stiffness of your structure?
2. Experimental design

    (a) How are the boundary conditions (loads and supports) applied to your specimen? Are your assumptions justified?
    (b) What maximum load do you expect to apply? Under this load, what maximum stress do you expect?
    (c) Under this load, what maximum deflection do you expect? Are the assumptions of your mechanical analysis still reasonably valid after this displacement? How could you verify that?
3. Measurement and uncertainty
    (a) What measurements will you make, and how?
    (b) How can you estimate the uncertainty of each of these measurements?
    (c) Will you measure displacement? If so, what is the smallest displacement you could reasonably measure, and how does it compare to your expected maximum displacement?
    (d) Will you measure or apply forces? If so, what is the smallest force you could reasonably measure, and how does it compare to your expected maximum applied force?
    (e) How will you calibrate your applied force? (How will you know what force you are applying, or how will you know that whatever you use to measure forces is accurate?
4. Troubleshooting
    (a) Have you tested out your experiment, even very roughly?
    (b) What difficulties did you run into? What are some potential concerns?
    (c) What simple design changes could you make, and what performance tradeoffs would result?

Lab survey questions

Please complete this survey **after** you have submitted your lab report. Participation in this survey will earn you 1 point towards your lab report score. As you answer the questions, **reflect on all aspects of the lab activity.**

Please indicate how much you agree or disagree with these statements based on your most recent lab experience in this course:

Scale: Strongly disagree, Disagree, Neutral, Agree, Strongly agree

1. I am in control of setting the goals for this lab activity.
2. I am in control of choosing the appropriate analysis tools to evaluate experimental data.
3. I have the freedom to create my best work for this activity.
4. I was sometimes surprised by the outcomes during this lab activity.
5. I learned something unexpected during this lab activity.

Please rate how confident you are that you can do each of the following things in an engineering lab:

Scale: 1: Not confident to 5: Very confident

1. Express my opinions when others disagree with me.
2. Achieve an equitable division of work within my group.
3. Overcome any problems I encounter during the experiment or analysis.
4. Interpret data taking into account experimental uncertainty.
5. Interpret graphs of experimental measurements.
6. Make accurate predictions about experimental outcomes.
7. Design an experiment to reliably measure mechanical properties.
8. Generate further questions based on my observations in the lab.