Re-inventing a Mechanical Properties of Materials Laboratory Course for Online Learning

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Abstract

The COVID-19 pandemic caused many institutions to shift from in-person learning to online delivery of course content, including laboratory courses. At the University of California, Davis, the Mechanical Properties of Materials Laboratory course instructors only had two and a half weeks to prepare for a Spring quarter conducted without any in-person interactions. With the rapid transition to online-only instruction, it was impossible to meet the learning goals of developing hands-on experimental skills alongside analysis and data communication topics. Instead, the instructional team reimagined the course learning objectives. A greater emphasis was placed on data analysis methods such as statistics. We also chose to prioritize written communication, including constructing arguments and problem statements. These topics were taught in guided one-hour discussion sections with the Teaching Assistants (TAs), while the weekly one-hour lectures focused on the labs' scientific content. This paper reports on the adapted course content and reflections from the instructor, TAs, and students.

1. Introduction

The COVID-19 pandemic disrupted higher education worldwide in March 2020. Colleges and universities abruptly stopped in-person instruction and instead required remote teaching. Instructors' challenges included preparing virtual lessons, learning videoconferencing software, and selecting appropriate graded assessments. At the same time, students' learning routines were disrupted as many returned home and were away from their peers; some students also lost the safety net that the university provided, such as reliable food and shelter [1]. Furthermore, both students and faculty were affected by limited internet connectivity and additional family responsibilities due to the pandemic. In March 2020, a "revised syllabus" circulated on the internet, which provided the following five guiding principles for a term interrupted:

1. *Nobody signed up for this*
2. *The humane option is the best option*
3. *We cannot just do the same thing online*
4. *We will foster intellectual nourishment, social connection, and personal accommodation*
5. *We will remain flexible and adjust to the situation*

--Brandon L. Bayne, 2020 [2]

The authors of this paper adopted these principles as they prepared for teaching in Spring 2020.

Remote laboratory courses are challenging to design due to the hands-on activities typically utilized for in-person instruction. Furthermore, laboratory courses are vital to the preparation and training of engineers. A 2002 colloquy identified thirteen objectives that are fundamental for all engineering teaching laboratories, including instrumentation, experiments, data analysis, communication, and learning from failure [3]. The literature further discusses the importance of maintaining these objectives in undergraduate programs with distance learning programs. However, the COVID-19 pandemic has caused some schools to teach lab courses entirely online without any in-person activities due to local health orders. Engineering programs took varied methods to adapt to the changes. One electrical engineering course mailed experiment kits to students [4], while a dynamics course replaced two experimental modules with machine-learning modules [5]. Redesigning these courses required applying B.L. Bayne's guiding principles (from above) as lab instructors aimed to foster student learning and be flexible to the situation since in-person lab sessions were not possible.

2. Course Information

Mechanical Properties of Materials Lab is a required, junior-level course in the MSE department at the University of California, Davis (UC Davis). Students must enroll concurrently in the separate Mechanical Properties of Materials lecture course. Additionally, as a prerequisite, students must have taken the introductory Properties of Materials course, which includes a laboratory component. The Mechanical Properties Lab course is offered annually and typically enrolls 30-40 students, primarily within the major. The instructional team consists of a professor, who serves as the instructor of record, and two or three Teaching Assistants (TAs).

2.1. Typical Course Offering

Before the pandemic, the three-credit course was scheduled as one hour per week of lab lecture and three hours per week in the laboratory; students wrote lab reports and analyzed data outside of class. Many lab activities are similar to those at other institutions: aging of aluminum alloys to evaluate precipitation hardening, mounting and polishing metallographic samples to relate microstructure and mechanical properties of brass, and measuring the viscoelastic properties of polymers. UC Davis also includes a nanoindentation unit that utilizes equipment available in the undergraduate MSE Teaching Lab.

2.2. Overview of the Revised Course

The instructional team reimagined the lab course in the *two and a half weeks* between the cessation of in-person teaching and the start of the Spring quarter. The entire class had to be conducted remotely, with no in-person activities for students. Instructors were only permitted on campus for teaching preparation (e.g., recording lab videos). We identified several priorities when redesigning the course:

- Emphasize student learning:
    - Change learning objectives to match the public health constraints.
        - Remove instruction on laboratory equipment and preparing metallographic samples.
        - Add instruction on technical writing.
    - Create a course structure that is clear and predictable to help students manage their remote work.
- Set reasonable expectations for the instructors:
    - Select learning activities that can be done in the short preparation time and leverage the instructional team's expertise.

These priorities reflected the effect of the pandemic on both the students and the instructional team.

The instructional team opted to reuse prior laboratory modules to ensure that each unit was well-planned. These modules already had lab manuals that provided background information, experimental procedures, and grading expectations. Data for these experiments was available from past course offerings, and the instructor and TA recorded videos of the experiments at the start of the term. Furthermore, the instructor was familiar with the common misconceptions and difficulties encountered when completing these labs. Reusing lab activities also allowed the instructional team to focus their energies on developing supplemental course activities.

The course structure was also adjusted to support student learning. Weekly three-hour labs were replaced by one-hour discussion sections led by one of the TAs. These sections alternated between writing and technical instruction in the course, with the two TAs each entrusted with one aspect of the class. The Technical TA, Gianmarco Sahragard-Monfared, was conducting graduate research in mechanical properties of materials and was experienced teaching Mechanical Engineering lab courses. In contrast, the Writing TA, Edward Conley, had tutored students on lab report writing as a prior TA in an introductory course, but did not have research experience in mechanical properties. The TAs leveraged their expertise to independently create the content for their respective lab sections. Homework assignments were also added to the course to reinforce basic concepts prior to students' submissions of the lab report. These changes balanced student learning with instructor workload.

For clarity in scheduling, the 10-week lab course was divided into five two-week units. A sample schedule for Unit 3: Viscoelasticity is given below in Table 1. For each unit, Monday's scheduled lab lectures were given synchronously by the instructor and recorded for students unable to attend. A pre-recorded video of the laboratory experiment was also uploaded to the course website. Students then attended a technical discussion one week and a writing discussion the other week. Attendance was required at these discussion sections, but students could select between the Tuesday and Wednesday offerings. Finally, each unit had graded homework due at the end of the second week of the unit, and the lab report was due the following week. Course meeting times were consistent throughout the term, and all deliverables were due on Fridays.

Table 1. Schedule of course activities for Unit 3: Viscoelasticity. The unit spanned weeks 5 and 6 of the course, with the lab report due the following Friday (Week 7). The Unit 2 lab report and Unit 4 instruction are included in parentheses to show the overlapping submission dates.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Week 5	Lab lecture	Technical Discussion	Technical Discussion	--	(Lab Report 2 due)
Week 6	Lab lecture	Writing Discussion	Writing Discussion	--	Homework due
Week 7	(UNIT 4)	(UNIT 4)	(UNIT 4)	--	Lab 3 report due

2.3. Technical Course Content

Most of the technical course content was taken from previous in-person offerings of the course. The weekly lab lectures provided an overview of the current lab module's scientific content,

such as discussing viscoelasticity theory before analyzing experimental data and writing lab reports on the topic. As described previously, the Technical TA led bi-weekly discussion sections that supported students in their analysis.
The five lab units were:

1. Basic Mechanical Testing
2. Nanoindentation
3. Viscoelasticity
4. Precipitation Hardening
5. Nanowire Simulations

A brief description of each unit is included below, highlighting the changes for the online-only version of the class.

2.3.1. Unit 1: Basic Mechanical Testing

This unit focused on measuring the mechanical properties of 6061 Al utilizing the tensile and cantilever beam tests. The first week focused on running tensile tests and analyzing a stress-strain curve for the material's Young's modulus, yield strength, ultimate tensile strength, and ductility. The content was reviewed from the prerequisite introductory course and was designed to activate students' prior knowledge.

Changes for Spring 2020
The Technical TA, Gianmarco Sahragard-Monfared, expanded the basic mechanical testing unit by adding a cantilever beam test. The Technical Discussion focused on this cantilever beam test. First, an example problem reviewed concepts such as bending stress, shear stress, and principal elements. Then students watched a video of the TA setting up and performing a cantilever beam test on a 6061-T4 aluminum beam that was anchored on one end and loaded on the other; strain gauge rosettes were mounted on the sample to measure strain. The video concluded with an example strain gauge rosette reduction to find the principal strains and the principal stresses by Mohr's circle and Hooke's Law. Data acquired by subsequent cantilever beam tests were provided to the students to complete the strain gauge reduction and calculate the Poisson's ratio of the material.

2.3.2. Unit 2: Nanoindentation

Nanoindentation is annually included in the Mechanical Properties of Materials course at UC Davis, building upon activities from the *uNano Workbook: Nanoindentation & Material Science* [6]. This unit covers nanoindentation theory and obtaining mechanical properties from the test data [6, 7]. Students determine the elastic modulus and instrumented hardness for one load-displacement curve to reinforce their understanding of the calculations. The microstructure-dependent properties of a material are also determined using data calculated by the software.

Changes for Spring 2020
For Spring 2020, the nanoindentation unit was supported by programs from KLA Corporation. One of the weekly lab lectures was replaced by a live webinar by Dr. Warren Oliver, one of the founders of nanoindentation. His webinar targeted university students in remote lab courses due to the pandemic and presented an overview of the nanoindentation technique [8]. He also

highlighted the capabilities of nanoindentation by showing results that incorporated advanced statistics with experimental data. The students also attended live nanoindentation demonstrations performed by a KLA employee for UC Davis. Students watched and asked questions as the KLA staff remotely ran the equipment and demonstrated the data analysis software. After the KLA session, the Technical TA guided the students through data analysis and curve fitting to determine the elastic modulus from nanoindentation data.

2.3.3. Unit 3: Viscoelasticity

This lab investigated the time-dependent response of polymers to applied loads. Tensile tests of acrylic and polyethylene were conducted at fast and slow strain rates to determine the materials' strain rate sensitivity. Students also investigated the stress relaxation of polyethylene, fitting the data to the Maxwell spring-dashpot model.

Changes for Spring 2020
The viscoelasticity unit was modified to respond to students' previous challenges to fit data to the Maxwell model, repeating their analysis many times without considering the model's limitations. This data analysis was the focus of both the Technical Discussion and the unit's homework assignment. The second change for this unit was to assign partners for lab report writing to promote student connections that are difficult to form during remote learning.

2.3.4. Unit 4: Precipitation Hardening

The fourth unit investigated precipitation hardening in 2024 Al to teach students the relationship between mechanical properties and heat treatments; similar labs are well-documented online [9]. In the single lab lecture (Week 7), the instructor presented an overview of particle strengthening and age hardening; only one lab lecture was included due to adjustments in scheduling surrounding the Memorial Day holiday.

Changes for Spring 2020
Minimal changes were implemented for the precipitation hardening unit. To account for the loss of one lab lecture, the Technical Discussion reviewed particle strengthening and coherent, partially coherent, and incoherent interfaces. A Ti-Al phase diagram was used to describe the expected microstructure throughout the solution treating and aging processes and show how these different microstructures influenced mechanical properties. Students selected partners for writing the lab reports.

2.3.5. Unit 5: Nanowire Simulations

The final unit simulated single crystal nanowires' deformation using the Nanomaterial Mechanics Explorer and related instructional materials on nanoHUB [10]. This module was already utilized in the lab course and easily transitioned to the online learning environment since the simulations are performed remotely through a web browser. Students compared the elastic modulus and yield strength from the simulation and reflected on the differences between the properties of bulk polycrystalline materials versus single crystal nanowires with varying crystallographic orientations.

Changes for Spring 2020
Prior course offerings found that students struggled with the concepts of preferred slip planes in single crystals and the differences between nanoscale and bulk properties. In response, the Technical TA session reviewed single-crystal slip and calculating the Schmid factor. The session also emphasized the differences between the properties of single crystals and polycrystalline materials and nanoscale and bulk properties.

2.4. Writing Discussion Sections

An ongoing effort in the MSE department at UC Davis is to thoughtfully integrate technical writing in the laboratory courses. Prior to the pandemic, instructors for several laboratory courses met to create a unified writing manual for use across the junior-year laboratory courses. Shifting to online instruction was an impetus to thoughtfully consider methods for teaching writing skills. The course instructional team agreed to create writing discussion sections, with all content prepared by the Writing TA, Edward Conley.

2.4.1. Unit 1: Components of a Lab Report

The Writing TA led students through the formatting and components of course lab reports (e.g., objectives, methods). Three activities were integrated into section. The discussion began with a quick writing activity where the students reflected upon the purpose and reasoning behind lab reports' structure. In following lecturing slides, students constructed three separate hypotheses for a given prompt and explained the hypotheses' general purpose. As a final activity, students were provided with densities of various metals and polymers with precision errors and then compared the data and discussed how the data addressed the given hypothesis.

2.4.2. Unit 2: Statistics and Writing

This discussion section's learning objective was to use the Student's T-Test to address the significance between two measurements and answer hypotheses. This level of statistical analysis was necessary for completing the lab assignments. The discussion section began with the history and procedure for conducting the Student's T-Test, with occasional questions to probe student understanding. Following this lecture content, the TA presented students with two situations where data was shown to be (1) significantly different and (2) not significantly different. Then the students described how to address both outcomes in a technical report. Following the discussion, the TA lectured about how to approach both situations. In a final activity, students used the Student's T-Test to confirm or refute a hypothesis based on a given confidence level. The practice problem was based on Philip K. Dick's novel *Do Androids Dream of Electric Sheep?* and several students appreciated the pop culture reference.

2.4.3. Unit 3: Collaborative Writing Tools

This discussion section covered how to access and manage citations for reports using the campus VPN and Mendeley citation manager. The lecturing component followed a stepwise procedure for accessing the VPN and operating the citation manager. The section had an open discussion about what makes a good reference, how to find them, and strategies to get started working with references if unfamiliar with the process. After the lecture component, the section discussed the upcoming lab report for the course and collaboratively found two relevant references and practiced using the citation manager to place the references in a Microsoft Word document. As a final activity, students spent ten minutes inserting basic equations for the volume and surface area of a sphere into a Microsoft Word document before the TA led them through the process.

2.4.4. Unit 4: Brevity in Writing

This discussion section's objective was to lead students through the process of condensing writing and provide tools for them to critically reflect upon their writing. Several reflective questions began this process and led to an open discussion of what makes individual sentences in writing meaningful. Students were then shown an example of condensing a paragraph about precipitation hardening, where the TA discussed his reasoning behind each change. As a final activity, students edited another paragraph on precipitation hardening and then shared how they condensed and improved the paragraph. The instruction emphasized the many ways to perform this work and for students to develop their own styles.

2.4.5. Unit 5: Error and Limitations

The focus of this final discussion section was to instruct students on meaningfully discussing experimental results. The section began with a conversation about the importance of significant digits in scientific writing and how they relate to measurements' precision. The lecture then reviewed error propagation equations, experimental precision and accuracy, and identifying sources of error. Interwoven in this lecture was an activity for the students to calculate the error propagation on a density measurement and open discussion about sources of equipment limitations for precision measurements. Following the lecture material, students were challenged to design experiments considering a single run experiment and a multiple run experiment. In this activity, students compared calculations of precision from known equipment parameters and standard deviation measurements. The session concluded with students answering questions about the precision and accuracy of a thermocouple and how to calculate them.

2.5. Course Assessment

The online course design was assessed through two methods: student evaluations of teaching (SETs) and a supplemental survey. The SETs were conducted during the final week of the term in June 2020 and had 24 respondents out of the 31 students enrolled in the course. Standard questions on the SETS include the overall teaching effectiveness of the instructor, prior course preparation, and the strengths and weaknesses of the instructor. A supplemental survey was distributed to the students in January 2021 to prepare for primarily online instruction in Spring 2021. This survey asked students about their perceptions of course content's usefulness, recommendations for teaching modes (e.g., asynchronous, recorded), and whether individual modules should be included in Spring 2021. This survey had eight respondents.

3. Student Perspective

In January 2021, students were surveyed about their perceptions of the three instructional components of the course: lab lectures, technical discussions, and writing discussions. As shown in Figure 1, more than half of respondents strongly agreed that technical discussions helped them understand course content and should be included in Spring 2021; seven of eight were favorable to these sessions. On the SETs, one student noted: "the mandatory [Discussions] with the TA really helped with understanding the topic.". Furthermore, students were more strongly favorable toward the technical discussions than even the lab lectures, based on the supplemental survey. Six of eight students agreed that the lab lectures helped them learn content and should be included in Spring 2021, but these responses were split between "Strongly Agree" and "Agree." Finally, students had the lowest perceptions of the writing discussions. Only half felt that these sections improved their writing, and 25% disagreed with the two statements that these sections improved their writing and should be included in Spring 2021. Note that one respondent answered "Strongly Disagree" to all six statements and did not show a preference towards any of the instructional components, so the significance of these responses is unclear.

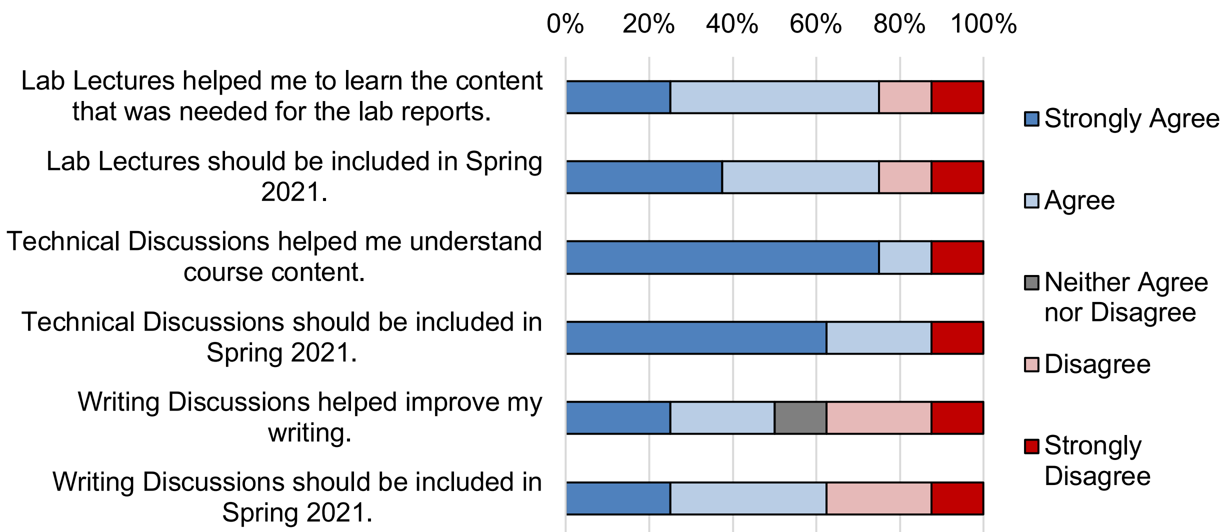

Figure 1. Student's perceptions of three instructional components: lab lectures, technical discussions, and writing discussions (n=8).

It is hypothesized that students' perceptions of the instructional components are due to the ease with which they recognized learning gains. The technical discussions included example problems related to data analysis, emphasizing typical misconceptions, whereas the lab lectures presented a higher-level overview of the background information for the lab. The Writing Discussion sections discussed general writing principles, but the applicability was more indirect. Students practiced a given topic, such as revising a provided paragraph for brevity, but they were expected to take the initiative to apply this when writing their lab reports. Although the instructional team equally valued all three components, students' opinions may have been swayed by the direct correlation between grades.

The preferred format of each course component was dependent on the specific activity. Figure 2 shows students' responses about the delivery mode of the lecture, technical discussion, and writing discussion; an asterisk (*) indicates the method utilized for the course. For the lecture and technical discussion, students preferred meetings that were optionally synchronous with recordings, followed by required synchronous, recorded meetings, and a lower preference for pre-recorded asynchronous content. However, students were nearly evenly split for the writing discussion as to whether they preferred a delivery mode that was synchronous or asynchronous and required or not required; no students preferred required attendance at a section without a recording. Interestingly, students strongly preferred live meetings for the technical discussion but had more mixed opinions for the writing discussion. Additionally, students' preferences only aligned with the lab lectures' actual instructional mode, not the two discussion components.

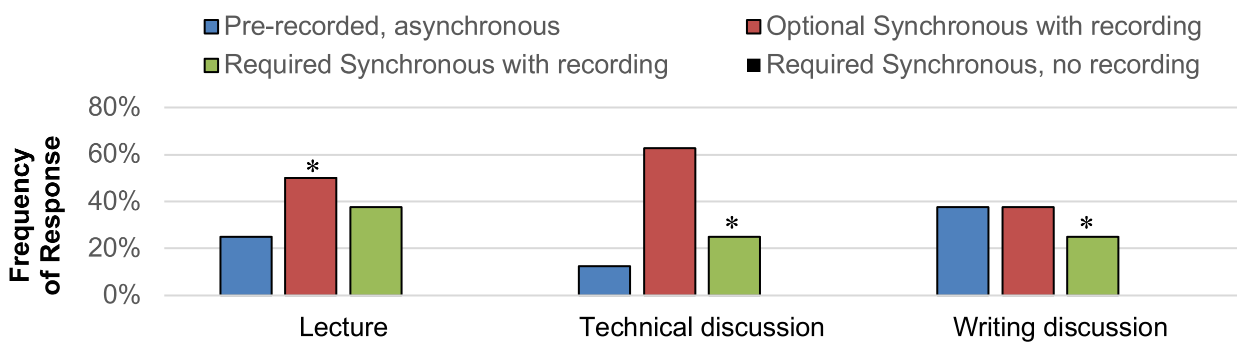

Figure 2. Preferred delivery mode for each component of the online course. The asterisk (*) indicates the mode that was utilized for Spring 2020 for each component. Students were permitted to select more than one option, so sums may exceed 100% for a given component (n=8).

Students were also surveyed about their preferred mode of instruction for laboratory experiments. Spring 2020 utilized pre-recorded, asynchronous demonstrations of the laboratory experiments. However, if in-person sessions were not possible in 2021, 87.5% (7 of 8) of students recommended live demonstrations with recordings, whereas only 12.5% (1 of 8) recommended pre-recorded, asynchronous demonstrations. No students recommended live demonstrations without recordings. One student commented that live lab sessions would allow them to ask the TA questions about the experiment, which is not possible for pre-recorded videos.

Finally, the January 2021 assessment also collected student's informal opinions about each of the lab units. As shown in Figure 3, the student consensus was that the traditional lab units (mechanical testing, viscoelasticity, and precipitation hardening) should be included in Spring 2021. However, students felt less strongly about the nanoindentation and simulation units. One of the favorable students did comment: "I would definitely love more simulations that directly try to tie us to the lab environment as much as possible."

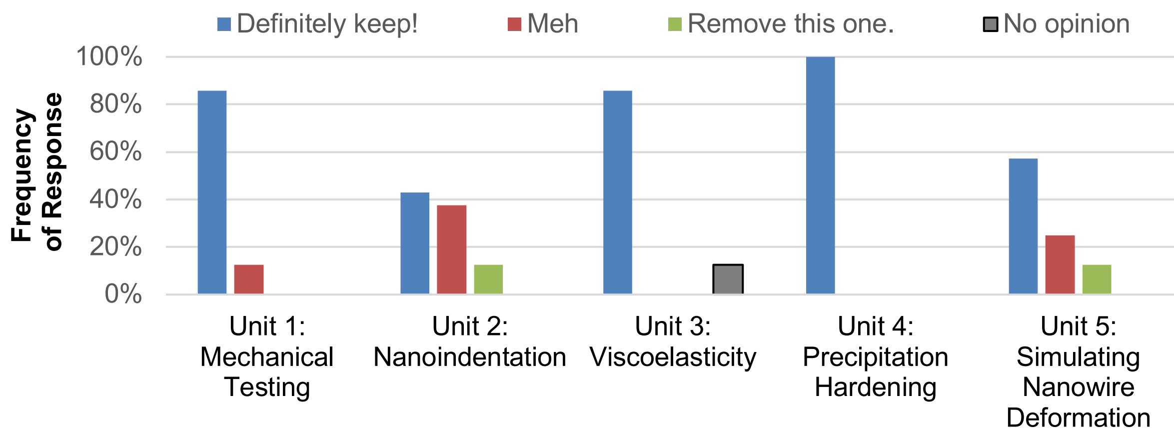

Figure 3. Students' opinions about whether each of the five lab units should be included in Spring 2021 (n=7).

This section describes the perceptions of students enrolled in the course. When reviewing the SETs, many responses focused on aspects of the course that were independent of the mode of delivery, such as students' workload and the time to receive graded reports. Several students noted the challenges of online learning, such as wanting more frequent recaps of content (beyond the weekly lectures) or workload concerns specifically related to online learning. Although student feedback should not be the sole driver in curricular changes, it is one factor of a supportive learning environment.

4. Reflections of Instructors

The reflections of the instructional team are given below.

Instructor: Susan Gentry
It was challenging to redesign a lab class to be offered virtually, with two and a half weeks' notice. Many of the instructional team's decisions reflect this short timeline. Replacing the laboratory time with Technical and Writing Discussions allowed us to focus on supporting students' lab report writing. Instruction of writing skills needs to be enhanced in our curriculum, and online learning gave us the opportunity to develop this instruction for the course. As the course instructor, my burden was eased by having two experienced TAs who provided input on the course design and developed their lesson plans based on our weekly team meetings. Finally, I am proud that the course was well-organized and predictable, as this is one of my weaknesses as an instructor. Supplemental at-home activities might have better engaged the students but would have risked the organization that was extremely important for online learning. Overall, I am proud of the instructors and students for adapting the course structure and teaching/learning materials science concepts over the quarter.

Technical TA: Gianmarco Sahragard-Monfared
In order to provide students with the best possible experience, technical discussions were developed around lab videos and supporting documents. Although it was evident that students wanted the hands-on experience of a lab, positive feedback was provided alluding to their

satisfaction with the virtual format. The ability to fast forward and rewind lab videos during the technical discussions proved to be an advantage of virtual teaching. On reflection, I think it would have been valuable for the students to watch the lab videos before the technical discussion sessions in order to give them more time to develop questions. This would lead to a more productive discussion and allow for a more efficient use of class time. During the lab, students learned about relevant mechanical testing techniques and related theory. I believe that, despite the unusual delivery method of this course, the students gained the same amount of knowledge as they would have with the conventional course format.

Writing TA: Edward Conley
Significant effort was put into providing several five-minute (or longer) activities interspersed with lecture material to maintain student attentiveness. These activities mainly took the form of quick writes and open discussions. This worked well for many students who were either actively engaged in the discussion or paying attention to the interactions over the zoom call. In retrospect, it would have been worthwhile to invest the time to create formative assessment mechanisms for the activities to promote student engagement. As the course progressed, students were able to utilize the tools taught in these sections to improve and develop their own writing styles. I felt that the design of the Unit 4: Brevity in Writing discussion section was particularly effective because it helped weaker writers develop their skills and challenged the more experienced students to improve.

4. Conclusions and Recommendations

The learning objectives and course structure of a Mechanical Properties of Materials Lab course were redesigned to fit the constraints of online learning. Although students lost opportunities for hands-on experimentation, these activities were replaced by supportive TA-led discussions focusing on technical and writing instruction. This course structure reflects the rapid, non-permanent nature of the online format; significant changes would be necessary if the course were to be routinely taught online after the pandemic.

Selecting an appropriate course structure requires consideration of both student perceptions and pedagogy. Students preferred course activities that were optionally synchronous and recorded since they were provided with the autonomy to create their own schedules for learning and the ability to review recordings. However, literature has noted students' difficulties to self-regulate learning in remote environments [11] and has linked procrastination to decreases in self-regulated learning [12]. The instructor must balance students' preferences with creating supportive structures that some students need to succeed. Similarly, students were more favorable towards the Technical Discussions as compared to the Writing Discussions. However, instructors consistently note weaknesses in students' writing. The disconnect between students' opinions, abilities, and pedagogy highlights the need for "instructor talk" in the classroom to reveal the pedagogical reasons for the course structure [13].

Reflecting on the online lab course in 2020 provides insight for the future. Most urgently, the feedback will be utilized for the Spring 2021 offering, which will again be mainly online. The only in-person component will be an optional comprehensive lab session where students run two experiments: nanoindentation and tensile testing. Lab lectures and discussions will remain remote synchronous, with optional and mandatory attendance, respectively. However, the Technical Discussions will include live demonstrations of the experiments for each unit. Importantly, the experiences from 2020 will also shape the future course design. Video recordings of the experiments and lab lectures will be routinely updated so that students can review these while preparing their laboratory reports. Additionally, the Writing Discussion modules will be developed into exercises that can be implemented into the course instructional time. Although the pandemic caused an upheaval in teaching and learning in 2020, the lessons about student learning should be retained for the future.

Acknowledgments

The authors thank KLA Corporation for their support of student learning during the pandemic, particularly creating an introductory webinar targeting students and hosting remote demonstrations of the equipment.

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