Remote advanced lab course: A case study analysis of open-ended projects

Jessica R. Hoehn,[1,2,*] Michael F. J. Fox,[1,2,3] Alexandra Werth,[1,2]
Victoria Borish,[1,2] and H. J. Lewandowski[1,2]

[1]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[2]*JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309, USA*
[3]*Department of Physics, Imperial College London, Prince Consort Road, London SW7 2AZ, United Kingdom*

(Received 19 May 2021; accepted 30 July 2021; published 20 August 2021)

The rapid transition to remote teaching in the spring of 2020 posed particular challenges for laboratory courses, which often involve students working hands-on with equipment in collaborative environments. Replicating in-person experiments was especially challenging for advanced lab courses that utilize specialized apparatus, which could not be accessed by students at home. However, physics lab instructors employed a variety of creative strategies to overcome these barriers and provide students access to lab-like learning in a remote setting. We report on one advanced lab course that used the transition to remote teaching to completely redefine the course goals and transition from traditional prescriptive labs to more open-ended projects. We conduct a case study analysis, triangulating among several data sources—survey responses and interviews from both instructor and students—to construct an in-depth understanding of the remote course and how students experienced it. Although we cannot necessarily generalize the results of this analysis to the entire student experience in the course due to the student response rate, the feedback that the course did receive from both students and the instructor was overwhelmingly positive, and the instructors are planning to retain the open-ended projects when the course returns to an in-person format. We find that the new open-ended projects afforded students opportunities to make decisions and think deeply about their experiments, which students report as contributing to their enjoyment and satisfaction with the course. Students had mixed group work experiences, with some describing positive and meaningful interactions and others describing group work as a source of frustration and stress. Additionally, some students missed being able to work hands-on with equipment, and some reported a high workload that made the course stressful. We discuss these student experiences and provide implications for both in-person and remote lab courses.

DOI: 10.1103/PhysRevPhysEducRes.17.020111

I. INTRODUCTION

In the spring of 2020, physics courses across the world had to quickly transition to operate remotely due to the COVID-19 pandemic. This posed particular challenges for lab courses, which often rely on students working hands-on with equipment in collaborative environments. Physics lab instructors employed a wide variety of creative approaches to overcome this challenge in order to continue to provide opportunities for students to access lablike learning during these challenging times [1–9]. From recorded videos of instructors conducting the labs, to sending equipment to students' homes, to engaging students in data analysis and scientific communication, the approaches used in physics lab courses and the elements that proved successful or challenging were highly context dependent [3]. In this context, we define remote labs to encompass any continued instruction of a course that was considered a lab course prior to the rapid transition to remote work, in which all students and instructors were not in the same physical location and were communicating asynchronously and/or synchronously online.

In this paper, we focus on one particular advanced lab course in which the instructors used the transition to remote teaching to completely redefine the goals and structure of the course by shifting from traditional prescriptive labs to more open-ended multiweek projects. Students liked the course overall, primarily because of the opportunities the open-ended structure of the projects gave them to make their own decisions and think critically about their experiments. The instructor also reported that

*jessica.hoehn@colorado.edu

the open-ended projects led to high student engagement, even in the remote format. In a broader investigation of remote lab courses during the pandemic, we find such student engagement in, and enjoyment of, the course to be uncommon [1]. This course thus presents an interesting case in which to explore and understand students' experiences more deeply. We conduct a case study analysis, triangulating among multiple data sources—instructor and student survey responses and instructor and student interviews—in order to gain an in-depth understanding of how this course implemented the projects in a remote format, and of students' experiences in the course. Our goals for this paper are to provide a rich description of the course context, highlight student voice, discuss the successful aspects and challenges encountered by both students and instructors, and provide implications for both remote and in-person lab courses.

We begin by presenting relevant background on remote labs and project-based labs (Sec. II) and describing the methodology for this study (Sec. III). Then, we provide a description of the institutional, departmental, and course context (Sec. IV) as well as the instructor's articulation of main course goals (Sec. V). In Sec. VI, we present and discuss students' experiences and perspectives as documented in closed- and open-response survey items, as well as from interviews. These student data form the bulk of our analysis, and are complemented by course-level results from the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) [10] (Sec. VII), and documentation of instructor perceptions of success and challenges (Sec. VIII). Finally, we conclude by discussing implications for remote and in-person lab courses (Sec. IX).

II. BACKGROUND

A. Remote lab courses

Lab courses are a crucial part of the physics undergraduate curriculum and in-person, hands-on, collaborative environments are ideal for achieving the myriad goals that lab courses seek to achieve [11]. Nontraditional lab experiences (i.e., remote, virtual, home-based, or distance learning labs) are not the norm in physics education, but are certainly not new. These types of lab instruction can present some possible benefits, such as providing more flexibility [12] and expanding access to laboratory work for students who are part-time, have disabilities, or have caring responsibilities [13]. In a comparative study of traditional in-person labs and online labs that used an Interactive Online Lab (iOLab) device for hands-on work, Rosen and Kelly report that there were no differences in students' epistemological beliefs about experimental physics or views about help seeking, but that the online option offers students a choice of their preferred format regarding social interaction [14]. Leblond and Hicks also describe an online lab course that uses the iOLab device and suggest that iOLabs coupled with an online course design that emphasizes teamwork, targeted feedback, and self regulation can provide opportunities for students to engage in hands-on, inquiry-based lab learning outside of the classroom [15]. Thus, there are increasing opportunities for remote physics lab courses to provide a complement to in-person labs, which may present potential benefits for student learning. However, other research concludes that remote lab courses *may* be detrimental to students' development of lab skills [16]. As such, any remote lab course must take care to consider both potential benefits and disadvantages to student learning.

Of course, creating and running a remote physics lab class, just like any other class, requires a lot of preparation, thought, and expertise around remote pedagogy. Unlike in the studies mentioned above, the switch to remote instruction in the spring of 2020, due to the COVID-19 pandemic, was sudden and unplanned. To distinguish from courses that were designed from the beginning to be remote, we refer to this situation as *emergency remote teaching* [17]. The community of physics lab instructors had to employ creative and resourceful approaches to rapidly transition their courses to be remote, while maintaining their learning goals [1,2]. Some of these approaches included using equipment like iOLabs [14,15] or sending kits home with students [9], having an instructor or teaching assistant in the lab manipulating the equipment while students direct them via video conference, using simulations to explore phenomena and collect data, sending students data already collected and having them focus on data analysis and communication, and more.

A few studies have looked at how this rapid transition to remote lab teaching impacted students. In a separate investigation of students' attitudes toward experimental physics, we found that, in a sample of introductory courses, students' scores on the E-CLASS [10] were no different in 2020 as compared to prior years [4]. We do, however, observe differences on individual survey items, including a possible shift toward the expertlike view that the role of experimental physics is not simply to confirm previously known results. In a study of students in Germany, Austria, and Croatia, Klein *et al.* report that students considered labs more successful when they collected their own data rather than worked with data that were provided to them [5]. Additionally, they found that first year students were less likely to perceive that remote lab courses were effective at helping them develop experimental skills than students who were farther along in their degrees. In contrast to our previous work [4], here we focus on an advanced lab course and conduct an in-depth qualitative investigation of students' experiences, discussing the ways in which both they, and their instructor, felt that the remote lab instruction impacted their learning and development of experimental skills.

B. Benefits of project-based labs

Project-based labs, in which students work in groups on a single experiment for several weeks at a time, are growing in popularity [18]. Such projects can have varying amounts of structure—sometimes instructors may define the topic or goal and students have to figure out how they will achieve the goal, while other times students are responsible for selecting the topic and defining the project from start to finish. The goals of project-based labs are often to provide students with authentic researchlike experiences and to focus on important aspects of experimental physics like teamwork and communication, preparing students for future careers in physics or science more generally [18–21]. Research in physics education demonstrates that projects can introduce students to real practices and skills of experimental physicists [21–23], impact students' views about experimental physics [24], increase students' confidence and competence around experimental physics tasks or skills [25,26], and support students' sense of ownership [27–29].

Engaging students in open-ended projects may also provide opportunities for student agency, a key element of ownership. In science education, there are a variety of definitions for agency [30], but generally it can be thought of as the "opportunity to make decisions to pursue a goal" [22]. Holmes, Keep, and Wieman describe the crucial role that agency plays in scientific practice, and discuss students' *decision-making agency* in instructional lab environments [22]. When students have to make decisions about their experiments or investigations in physics lab courses, they are afforded agency within that specific context. They might have to define a research question, decide what equipment, measurement techniques, and analysis methods to use, or determine how to present the results. Opportunities for this type of agency may be available in project-based lab courses with varying structures and amounts of instructor guidance [22], but traditional prescriptive labs typically do not afford students the opportunity to make many decisions since they require students to follow a manual or predefined, step-by-step procedure. The construct of agency is complex and constantly evolving, encompassing practices of both individuals and social groups [30]. In this paper, when we use the term agency, we are referring to the decision-making agency that students have within the confines of the social structure of one particular lab course, and we do not consider macrostructures beyond this local context.

In the transition to emergency remote teaching during the COVID-19 pandemic, some instructors incorporated projects as part or all of the remote course. Shivam and Wagoner [6] describe an introductory algebra-based course in which students each did three different remote experiments: a recorded experiment in which students watched videos of instructors performing the experiment and then used their observations to develop a model of the system, a virtual experiment in which students used PhET simulations [31] to make measurements and analyze data, and a three-week-long project in which students had a choice of using a web applet to experimentally answer their own question, designing and conducting an experiment using physical household materials, or using the Algodoo [32] software to design their own "scene." Students reported that they learned the most from the project because they had to be involved at every step, making decisions and thinking critically about their experiment. Additionally, students in this study found the project and virtual experiments to be most enjoyable. In a physics and information science course, Bradbury and Pols [7] implemented open-inquiry projects in which students defined their topic, research questions, and methods, with guidance from the instructor. One of the major goals of their course was to have students experience an iterative cycle of scientific research, and the authors report that the open-inquiry structure was one key factor that led to the success of these projects in the emergency remote teaching context. In a first year lab course, Pols describes a transition from prescriptive to more open-ended lab activities for which students were given a research question and had to design their own experiment [8]. They report that this course structure was successful in getting students to engage in scientific inquiry.

Similar to each of these three examples, the case study that we present here is a course that transitioned from traditional prescriptive labs to more open-ended projects that afforded students' opportunities for decision-making about their experiments and opportunities to experience the iterative nature of experimental physics. Our case differs from these examples in that it is an advanced lab course for physics majors and, unlike in Refs. [6,7] (but similar to Ref. [8]), students did not choose their own topic or research question, but rather designed their own experiment to solve a particular problem posed by the instructor. Additionally, unlike in the introductory lab courses described in Refs. [6–8], this course added open-ended tasks to experiments utilizing complex equipment typical of research labs, thereby retaining the opportunity for students to learn about technical equipment and allowing for these changes to more easily transfer back to the in-person version of the course.

III. METHODOLOGY

A. Data collection

As part of a larger study of emergency remote physics lab courses, we collected several forms of data beginning in March 2020, when many courses transitioned to remote teaching. First, we administered an online survey to physics lab instructors that contained both closed- and open-response questions about their course and their experience with the transition to remote teaching. We sent the survey to professional listservs related to laboratory instruction as well as to instructors currently administering the E-CLASS in their courses; we received responses from 106 instructors representing 129 different courses.

The E-CLASS is an instrument that probes students' attitudes and beliefs about experimental physics, and is used worldwide by instructors to evaluate and improve their lab courses. Each semester, the survey is administered pre- and post-instruction to a few thousand students in approximately 50 courses. In the Spring 2020 term, we appended a set of additional questions to the end of the standard postinstruction E-CLASS, which included both closed- and open-response questions about students' experiences with the transition to remote teaching of physics labs. We refer to these questions as the *remote lab survey questions*. Closed-response questions asked students to identify the activities they engaged in and challenges they encountered, as well as to respond to a series of Likert scale statements. A few example statements include the following:

(i) I liked the remote lab class.
(ii) Compared to in-person labs, remote labs were better at helping me learn laboratory skills.
(iii) Compared to in-person labs, remote labs were better at enabling me to work at my own pace.

The answer choices given for the Likert scale items were strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree. For the remainder of the paper we refer to the "neither agree nor disagree" option as "neutral," for the sake of brevity. There were four main open-response questions:

(i) Describe your favorite aspect of the remote lab class
(ii) Describe the thing you missed the most about in-person lab classes
(iii) Please give an example of how the transition to remote lab instruction impacted your learning
(iv) Describe the biggest challenge that you encountered in the remote lab instruction environment

From an initial review of the instructor survey results and student responses to the remote lab survey questions, we identified 10 instructors to interview to gain a more in-depth understanding of their remote lab course. We selected the specific instructors to represent a range of course types, institutional contexts, and approaches to remote labs. The interviews were conducted by the first author via Zoom. Interview protocols were unique to each instructor based on the information they had provided about their course in the instructor survey; the overall goal of the interviews was to gain a thorough understanding of a few specific courses, including how the remote course was structured, why instructors made the decisions they did in making that transition, and elements that worked well or were particularly challenging. Details of the specific interview protocol used for this paper are provided in the following section.

From an initial review of the instructor interviews, we identified 3 courses from which to recruit students for interviews. Again, these courses were selected to represent a range of course types, institutional contexts, and approaches. We sent an email to the students in each course that described our overall research study, asked for interview volunteers, and stated that the purpose of the interviews was to gain a better understanding of students' experiences in these remote courses. Participation in the interviews was voluntary, the instructors of each course did not know which students participated in the interviews, and students were compensated for their time. Student interviews were conducted by the first author via Zoom. The student interview protocols were unique to each course; we provide the details in the following section.

B. Case study analysis

While each of these data sources—instructor survey, student responses to the remote lab survey questions, E-CLASS results, instructor interviews, and student interviews—has been, or will be, used in other analyses [1,4], this overall data collection process was driven by a case study approach. From the three courses for which we have all five streams of data, we selected one for a case study analysis to be presented in this paper. This particular course was selected because it transitioned from traditional prescriptive labs to more open-ended projects in parallel with the transition from in-person to remote teaching, and the student feedback about the course was overwhelmingly positive (e.g., students reported on the remote lab survey questions that they liked the remote course, a result that is uncommon among other data we have collected). The goal of this case study analysis is to understand all the details about how this course operated and how that impacted students' experiences. We chose a case study methodology to achieve these aims because it is particularly useful for constructing a holistic and in-depth understanding of a situation or phenomenon, through triangulation of multiple data sources [33].

The course we analyze for this case study had a team of instructors comprised of three lab staff members, one faculty member, and six graduate teaching assistants. The primary instructor, one of the staff members who is also the director of physics instructional laboratories at his institution, Joel (he/him, pseudonym), filled out our instructor survey (both closed- and open-response questions) and participated in an interview. Joel self-identified as a white man and has been teaching this course for over 20 years. The interview protocol was designed to last one hour, but Joel opted to keep the interview going longer (for approximately an hour and a half) because he wanted to share more information about the course. The instructor interview protocol was informed by the information Joel provided on the instructor survey. We asked about logistical details (e.g., Who was on the instructional team and what were their roles? How did you make use of technology such as Zoom? How were student groups assembled?), the process of redefining goals for the course (e.g., What were the learning goals and how did they differ from the in-person course? What was the process like to define those goals?), specifics about the open-ended projects (e.g., What were some example projects students worked on? How did remote data collection work?), and successes and challenges they encountered (e.g., What were the most successful aspects of the course? Can you elaborate on some of the challenges you reported on the survey?).

Out of an enrollment of 60 students, there were 28 students who completed the standard post-instruction E-CLASS (27 matched pre-post responses), and 22 of them also responded to the closed-response remote lab survey questions. Sixteen students responded to at least one of the open-response remote lab survey questions; each of the four open-response questions had between 12–14 responses, which ranged from a few words to a few sentences. In the Spring 2020 quarter, 70% of students in the course identified as men and 30% identified as women. We do not have access to race or ethnicity information for the course as a whole. All three students who volunteered to be interviewed in this study were junior physics majors. Samuel (he/him, pseudonym) self-identified as a white and Asian man, Mei (she/her, pseudonym) self-identified as an Asian woman, and Amy (she/her, pseudonym) self-identified as an Asian woman. The student interviews lasted between 55 and 59 min. The student interview protocol was informed by the information we received about the course from both the instructor survey and interview. We asked students about their general experience with the remote course (e.g., What were your favorite aspects? What was most challenging? How did the remote quarter compare to the prior two quarters?), details of their projects (e.g., What projects did you work on? How did you make decisions when designing your own procedures? Did you make any revisions to your plan or experiment?), their experiences with remote collaboration (e.g., How did your groups divide up the work? What did you get out of the meetings with your group members, TAs, and instructors?), and opportunities for agency (e.g., Do you feel like you had control over your own learning in the course?).

To conduct the case study analysis, we first reviewed the instructor survey and instructor interview data in order to construct a thorough understanding of the course context (Sec. IV) and goals (Sec. V), as well as Joel's perspectives on successes and challenges in the course (Sec. VIII). Next, we looked at the class average E-CLASS scores over the last three years to see if there was a difference in the pre-post shift in the 2019–2020 year as compared to prior years. We also looked at an individual E-CLASS item that aligned with the one of the goals of this course to determine if it had shifted from prior years. These results do not feature heavily in our analysis, but we do report them as one way to assess impact of the remote course.

Next, we reviewed student responses to the remote lab survey questions. For the closed-response questions, we identified a subset of items that either had a bimodal-like response with a majority of the students falling in the extremas or that we felt might be particularly related to students' experiences with the open-ended projects. We did not conduct any statistical tests on the closed-response data—instead, we use the results as a complement to the open-response and interview data, with the latter providing meaning and context for the closed-response results.

For the open-response questions, we conducted a coding analysis of students' responses in order to identify common themes in the experiences that students shared. Through an iterative process, we identified 13 emergent codes categorized into four main themes (Sec. VI). Upon creating the codebook, we conducted an interrater reliability study in which two independent researchers coded a subset of the data (20 student responses, out of the total 53). The Cohen's kappa was 0.96, and the two raters reached 100% agreement on all codes after discussion. The first author then coded the entirety of the open-response dataset. After we had identified the four main themes present in the open responses, we reviewed the transcripts of student interviews and identified the interviewees' experiences and perspectives related to those four themes.

In order to achieve a holistic and in-depth understanding of students' experiences in the course, we triangulate among the closed-response, open-response, and interview data from students. In Sec. VI, we present the results of analysis of each of these data sources together, organized by the four main themes from the open-response coding. We discuss how the closed-response, open-response, and interview data speak to each of these themes. Then, to complement the student experiences highlighted in the analysis, we present a few results from the E-CLASS (Sec. VII) and the instructor perspectives on successful and challenging aspects of the course (Sec. VIII).

Upon completing a draft of this paper, we conducted a member check with Joel. He and the other members of the lab staff reviewed our description of the course context, as well as our characterization of instructor perspectives about successful and challenging aspects of the course in order to ensure that we were portraying their context and views accurately. Resulting from this member check was only one minor change to our understanding of the course context (specifically, the length of the quarter).

C. Ethical considerations

Before conducting this study, we considered whether it was ethical to conduct education research during a pandemic and how we might do so in a way that was beneficial to the physics community, while minimizing any potential harm or burden to research participants. The benefits of conducting this research include documenting the experiences of students and instructors, thereby valuing them as members of the physics education community, taking lessons learned from remote lab instruction to inform future lab courses (both remote and in-person), and identifying long-term implications for expanding access to physics labs. Instructors employed many creative strategies to overcome the barriers of remote instruction during a challenging term; some of these approaches could prove promising for expanding what it means to learn and do physics as part of the undergraduate curriculum. We believe that documenting these approaches will benefit the physics education community.

In designing this research study, we identified three primary potential concerns. First, we were particularly attuned to the fact that students and instructors in our study may be suffering from personal physical and mental health crises due to the pandemic, have increased family or childcare responsibilities, be experiencing financial strain due to the pandemic, or have limited access to necessary resources to complete their work (e.g., internet, quiet place to work). In conducting this research, we risked adding to those burdens. Second, we were concerned about the people who would not be able to participate in the research due to these additional barriers, and thus would not have their experiences and perspectives represented. The third concern was that research participants would be asked to think, talk, and/or write about stressful circumstances or emotional topics during an already traumatic time, thus exacerbating the emotional toll of the pandemic. We took care to mitigate each of these concerns through every step of the research process, and concluded that in doing so the benefits of conducting this research outweighed the risks.

We worked to mitigate the first concern by minimizing additional time asked of participants and to ensure that participation in every aspect of the research was voluntary. In writing the instructor and student survey questions, we strove to minimize the amount of additional time we were asking people to spend by limiting the number of questions. As such, we included only questions that we felt would provide information of benefit to the physics education community. In particular, we limited the number of open-response questions. For both instructors and students, participation in this research was voluntary and instructors could opt out of having their students see the remote lab survey questions at the end of the standard E-CLASS. For students who were already completing the E-CLASS as a regular part of their course, and whose instructor did not opt out of including the additional questions about remote instruction, the additional questions were optional. Indeed, some students in our case study completed the standard E-CLASS and then opted not to continue to the remote lab questions. Student interviews were also voluntary and were completely disconnected from the course (they took place after the course had been completed and instructors did not know who participated in interviews). As is standard practice, we compensated students for their time and notified them that they could choose to leave at any time or choose not to answer specific questions.

Beyond making it as easy as possible to participate in the research (given the existence of adequate time and resources), we did not have much control over who was able to participate in our study. As such, the concern about excluding participants who were being impacted more severely by the pandemic remains a limitation of our study. We remain cognizant of this fact throughout our analysis, and take care not to make claims of generalizability of the experiences presented in this paper to all of the students in the course.

To minimize the risk of participants feeling like they needed to discuss potentially traumatic situations, we did not ask participants about how the pandemic was impacting them other than through their experiences with remote instruction. In the interviews, we were happy to listen and engage in conversation around these topics if the interviewees wanted to, but we did not ask them to be vulnerable with a stranger if they did not want to be. As with any interview study, we strove to build rapport with interview participants and conducted the interviews in a semi-structured manner such that they flowed like a casual conversation. In this way, we attempted to make the interview a space for connection in which instructor and student participants could guide the conversation.

Throughout our overall study, we found that instructors were eager to share their experiences and to see the results of our research that might inform their ongoing remote lab courses. Similarly, the three student interviewees for this case study seemed eager to share their experiences with us. They all expressed gratitude for the opportunity and said they were eager to contribute to the research that might benefit other lab courses (both remote and in-person). Thus, we feel that at least for the students and instructors we interviewed, the benefits of participating in the interview outweighed any burdens.

D. Limitations

As with any case study analysis, the analysis we present in this paper cannot be generalized to a broad population or wide variety of contexts. Instead, we provide detailed contextual information such that readers can determine how the results from this case study may or may not apply to their own contexts. We also cannot necessarily generalize the results of this analysis to the entire course. Out of a total enrollment of 60 students, we had 28 post E-CLASS responses, 22 closed-responses to the remote lab survey questions, 16 open-responses, and 3 interviews; we do not know how representative this sample is of the whole course. However, regardless of the generalizability to the whole course, we do find it important and valuable to document individual students' experiences, noting that other students may have had different experiences. The low response rate to the standard E-CLASS is typical for this particular course. Over the last three years, the response rate on the post-instruction E-CLASS (end of the spring quarter) ranged from 27% to 53%. Thus, the low response rate in the Spring 2020 quarter is likely not a result of just the emergency remote instruction situation.

Another limitation of this study, as mentioned in the prior section, is that some students may not have had the time, energy, or resources (e.g., good internet connection) to fill out an online survey or participate in an interview due to the constraints and stresses of the pandemic or otherwise. We worry about whose perspectives are effectively being excluded from this research because of the disproportional burden of the pandemic they may have been carrying. In making conclusions from our analysis, we remain cognizant of this fact and focus on the experiences of the individuals who were able to share them, noting that others may have had different experiences. This is a limitation of the study, and of conducting education research during a pandemic in general.

IV. COURSE CONTEXT

The case we report on here is from a selective, private, multiracial, Ph.D. granting institution in the United States that operates on a quarter system. The physics department employs a three-person staff who are in charge of running the instructional laboratories (developing curriculum, setting up and maintaining apparatus, and coordinating with faculty assigned to teach courses with a lab component). The course that we analyze for this case study is the third quarter of a three-quarter advanced lab sequence, all of which are taught primarily by the lab staff. Additionally, there are six graduate teaching assistants (TAs) selected to help guide the students through their experiments in this course. The course typically enrolls 60 junior physics majors.

Historically (pre-2020), the course included traditional guided labs; students worked in groups to conduct three different experiments each quarter, each of which entailed working through a detailed, prescriptive lab instruction manual. In the Spring 2020 quarter, along with most physics courses across the United States and the world, instructors had to quickly adapt this course to be offered remotely due to the COVID-19 pandemic. The transition to emergency remote teaching occurred in between the winter and spring terms. Instructors had approximately two and a half weeks to adapt course materials and make arrangements for a remote version of the course. The spring quarter was shortened by one week, from 10 weeks to 9 weeks.

Over the last few years, the lab staff at this institution have been redesigning all of the laboratory curricula to be more in line with research-based pedagogy, beginning with the introductory lab courses. As of the 2019–2020 academic year, they had not yet made any major changes to the advanced lab course, which had been operating in the traditional guided lab format for around 50 years. In March 2020, faced with the challenge of adapting all of the lab courses to be taught remotely, the instructors significantly modified both the goals and structure of the advanced lab course. Joel described using the transition to emergency remote teaching as an opportunity to try something that they would not otherwise have been able to do in a normal quarter due to local departmental constraints.

In the remote version of the course, students worked in groups of three on two four-week-long projects. The course was entirely asynchronous except for weekly meetings that each group of students had with a graduate TA and instructor (i.e., there were no lecture components or whole-class sessions, which are not present in the in-person version of the course either). In preparation for the spring term, instructors identified six different projects that would be amenable to remote operation (e.g., an experiment centered around aligning optics did not meet the criteria of being amenable to remote operation). Each of the six projects used equipment that students were already familiar with from experiments they had conducted in the prior two quarters. Some projects had students do a deeper investigation of an experiment they had done before, while others involved doing a new experiment with equipment they were already familiar with.

An example of a project that was a deeper investigation of a previous experiment was a laser optics experiment doing Doppler-free saturated absorption spectroscopy with rubidium. When students conduct this experiment in the first two quarters of the course, they all get results with systematic error, but do not have time to explore the reasons for that error. The remote project offered students an opportunity to more deeply investigate sources of systematic error in this experiment. As a starting point, instructors gave students a couple of suggestions for things to investigate (energy calibration and detector response) and students had to come up with ways to minimize the systematic error.

An example of a project that involved a new experiment with familiar equipment was a total cross-section measurement for Compton scattering. Many students had previously completed a standard Compton scattering experiment in which they measured scattered photon energy as a function of angle. A more sophisticated version of that experiment, typically used in graduate lab courses at this institution, is a Klein-Nishina total scattering cross-section measurement, which involves taking into account the incident flux on the scatterer, the geometry of the scatterer, and the detector efficiency as a function of energy. The instructors simplified a few aspects of this more sophisticated experiment and used it as one of the remote projects. Other projects included a thermal neutron study experiment, single photon interference experiment, Mossbauer spectroscopy, and a measurement of the cross section of gamma rays for aluminum.

In contrast to the traditional guided labs students had experienced in the first two quarters of the course, these projects were much more open ended. Groups of students were assigned a project based on the experiments and equipment the students were familiar with from the prior quarters. Instructors defined the overall experimental problem or question (e.g., investigate sources of systematic error), and it was up to students to determine how they would go about solving that problem. Each group used a Wiki to facilitate collaboration and document their progress and experimental designs. Some groups also supplemented this with a Slack channel used for group conversations. In order to complete their projects, students could design experiments and submit data collection requests via a page on their Wiki. Instructors would then go into the lab in-person and collect the data requested by the students. Since instructors had to navigate public health restrictions, there was a two-week period in the middle of each project period in which they were able to collect data. Students were able to submit multiple requests for data within that time (i.e., collect initial data, analyze it, make changes to the procedure or data collection request, and collect more data). In the weekly group meetings, TAs and instructors would provide guidance to students, allowing them to explore and determine their own procedures and analysis methods, but not letting them get stuck "spinning their wheels" for too long. At the end of each project, each student wrote an individual lab report, which focused on discussing the students' decision making as opposed to discussing why the results were as expected, as the students had done for lab reports in prior quarters.

The other component of the course (in addition to the two four-week-long projects) was a *Physical Review Letters* style article the students wrote about an experiment they had conducted in a prior quarter. Instructors had been planning to include this new element since the beginning of the Fall 2019 term (i.e., it was not a result of the transition to remote teaching), and it replaced oral presentations that used to be included in the course. In the fall and winter quarters, instructors talked with students about the difference between journal articles and lab reports and formed small journal clubs in which students read scientific papers and talked about what they liked and did not like about the writing, key elements of a good journal article, etc. In the spring quarter, students selected an experiment they had completed in a prior quarter, wrote a first draft, engaged in a peer-review process in which every student reviewed two other papers, and then turned in a final draft along with a one page summary of how they addressed reviewer comments. The students relied heavily on the peer-review comments to help them craft their final papers, as the instructors only had time to read and provide feedback on the final drafts. Joel commented that the implementation of this writing and peer-review process was no different than it would have been had the course operated in person.

V. COURSE GOALS

The instructional team viewed the transition to remote teaching as an opportunity to transform the advanced lab course to be more in line with research-based practices, something they had been wanting to do for several years, but had not yet had the time or departmental consensus to accomplish. Despite the stressful circumstances and short timescale with which they had to prepare a remote course, Joel described feeling excited at having the freedom to modify the course as they wished. He said,

> *"we regarded this as an opportunity to try something totally off the wall that sounded great on paper, but would never have flown in a normal quarter…we felt actually no stress or pressure over this whole thing. It was actually liberating because everybody understood we have to try something new anyway, so we thought, part of it was, you know, how would we like this course to work ideally? And try to incorporate some of those things. So from that point of view I think this turned into a way to explore alternative methods of running the course that was successful enough that we're going to keep a lot of it."*

In the interview, Joel articulated four main goals that the instructional team had for students in the course: (a) collaborate as a group to solve a problem, (b) figure out their own path to work through the problem, (c) experience the iterative nature of experimental physics, and (d) move away from the mindset of striving to achieve a particular result. Though the past versions of the course involved working in groups, the nature of the group work was significantly different in the remote version of the course—rather than working together through a detailed lab manual to achieve a specific result, students now had to collaborate on designing experiments and procedures and choosing analysis methods in a situation that did not have one correct answer or method. As we discuss in the results below, students also picked up on this fundamentally different emphasis on collaboration.

Regarding the iterative nature of experimental physics, Joel explained in the interview that a physicist typically does not go into the lab knowing exactly what measurement they need. Instructors expected students to have multiple requests for data within each project; they wanted students to collect data, work with it, gain some insight about the experiment or the problem, and then refine their understanding of the data they needed, and collect more. Joel said, "this iterative process, which is the way real experimental science works…was one of our primary goals for the course, because [students] don't get that experience in the traditional format."

Lastly, the instructor explained that it was difficult to get students out of the mode of thinking that there was a particular answer they were looking for in each project,

TABLE I. Responses to a subset of the Likert scale items about the remote lab course administered at the end of the E-CLASS. We present the percentage of students that answered each item with *strongly disagree*, *disagree*, *neutral*, *agree*, or *strongly agree*. $N = 22$, though some questions only had 21 responses. Numbers are rounded to the nearest percent.

Survey item	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Rate how much you agree with the statement, "I liked the remote lab class."	5%	5%	27%	45%	18%
Compared to in person labs, remote labs were better at…					
…enabling me to design a procedure (i.e., choosing what I would do or what question I would answer).	0%	0%	10%	33%	57%
…enabling me to choose which tools/materials to use to complete coursework.	5%	24%	38%	19%	14%
…enabling me to work at my own pace.	0%	23%	14%	50%	14%
…enabling more productive collaborations with my classmates.	18%	18%	27%	18%	18%
…enabling more enjoyable collaborations with my classmates.	23%	23%	27%	23%	5%
…helping me learn laboratory skills.	23%	55%	14%	9%	0%
…providing clear expectations for completing coursework.	9%	45%	41%	5%	0%

especially after they had completed two quarters of the traditional format of the course in which the labs were quite prescriptive. The instructional team hoped to guide students away from looking for a particular answer and toward a more authentic engagement with experimental physics. Students' grades for the projects were not dependent on a particular result that they achieved, and TAs and instructors coached students to write their lab reports in a style that emphasized their own decision making rather than proving to the grader that they did the experiment correctly and got the right number.

VI. STUDENT PERSPECTIVES

The overall student feedback on this course was positive. As shown in Table I, 63% of students (out of the 22 that responded to the remote lab survey questions) agreed or strongly agreed with the statement, "I liked the remote lab class," and only 2 students disagreed. Further, in the open-response questions a few students commented that the model used for the remote course was beneficial and should be continued when courses return to be offered in person. For example, in response to the question about how the remote course impacted their learning, one student wrote, "I think I got a lot out of this quarter. I don't think it negatively impacted my learning." Another student commented,

> *"I think there were things about the remote quarter that were better than the in-person quarters. I believe this model for the class should be adapted to the in-person setting and replace the normal third quarter."*

This general positive sentiment about the course was unexpected given the stressful and unusual circumstances in which students were being asked to learn experimental physics remotely. In a sample of 2272 students from 49 lab courses during Spring 2020, the mean on the "I liked the remote lab class" statement was 0.788 when we collapsed to a three-point scale and assigned Disagree $= 0$, Neutral $= 1$, and Agree $= 2$ ($\sigma = 0.86$, SE $= 0.018$). For our specific course, on a three-point scale, the mean for this item was 1.52 ($\sigma = 0.68$, SE $= 0.15$). These results, along with students' comments on the open-response questions, motivated us to look more in depth at this course in the form of a case study analysis to investigate the specific aspects of the course that students liked and achieve a more in-depth understanding of their experiences.

Below, we present the results within four main themes that emerged from our coding analysis of open responses: open-ended structure of projects, collaboration, no hands-on work, and workload and stress. Within each theme, we triangulate the results of three data sources from students—closed responses, open responses, and interviews—presenting our analysis and discussion of the three data sources together. Table I presents the data from the closed-response questions that we include in this analysis. The codebook for the open-responses is presented in the Appendix and in the following sections.

A. Open-ended structure of projects

The central feature of the remote version of this course was the open-ended structure of the projects, which provided a striking contrast to the prior two quarters that centered around traditional prescriptive labs. In this section, we present and discuss results on how students engaged with the projects, the benefits of the open-ended structure that students report, and then briefly mention connections to other themes that will be discussed in subsequent sections.

The open-ended structure of the projects provided students opportunities to make their own decisions regarding their experiments. They report positive experiences in the course due to this open endedness, which they describe as being beneficial and enjoyable. As shown in Table I, 90% of students who responded to the closed-form remote lab survey questions agreed or strongly agreed that the remote lab was better than the in-person lab at enabling them to design a procedure. No one disagreed with this statement. In the in-person course in which students followed detailed lab manuals, there was likely little to no opportunity for students to design their own procedures. In contrast, the remote projects required students to come up with their own ideas and methods to achieve the overall experimental objective set by the instructor.

In addition to being afforded the opportunity to design their own experiments and procedures, some students also had the chance to choose what tools and/or materials they would use. In response to the statement that the remote lab course better enabled students to choose which tools and materials to use in order to complete coursework, students' responses were roughly evenly distributed across disagree, neutral, and agree (Table I). We suspect that this depended on the specific projects students worked on. For some projects, the instructors determined ahead of time which equipment students would use and students had to decide how they wanted to use it or what data to collect. For other projects, students may have had to make some decisions about apparatus or data analysis methods to use.

The most common thing students talked about regarding the open-ended projects was that they appreciated the opportunity to design their own experiments. In the coding analysis of the open response data, the most prevalent code was *liked experimental design* (10 out of 16 students). This code was applied when a student directly mentioned designing their own experiments or procedures or talked about specific aspects of experimental design, including choosing what data to collect. All of the instances of students talking about experimental design were positive—they spoke about this aspect of the course as their favorite aspect, something they enjoyed, and/or something that was beneficial for their learning. For example, one student wrote, "It was interesting and useful to think about designing experiments rather than just following a pre-established procedure." Further, two students spontaneously noted in their responses that the remote course had an explicit emphasis on experimental design (*experimental design emphasized in course* code), aligned with the instructor's stated goal of having students figure out their own method of addressing the experimental problem or question.

Affective outcomes are often explicit goals of lab courses [34], and especially in the stressful circumstances of Spring 2020 the fact that many students reported enjoying the chance to engage in experimental design (and enjoying the course overall) is one major success of the transition to more open-ended projects in this remote course. All three interview participants said their favorite aspect of the course was the independence that the open-ended projects afforded them. They said they liked the flexibility and having the opportunity to ask and answer their own questions rather than having to follow specific instructions. For example, in describing why the open-ended structure of the projects was his favorite aspect of the course, Samuel said in the interview, "it felt like I was doing a lot more, like it was actually me thinking through a problem as opposed to just being told to take some data, which I thought was more engaging."

Samuel's sentiment is aligned with the *critical thinking required* code from the open-response coding analysis. Four students in the open-response dataset talked about how the open-ended structure of projects required them to engage in critical thinking or to think independently and deeply about their experiments, which they saw as positive or beneficial. For example, one student wrote,

> *"I also learned to think more about experimental procedures since we have to give the data collection instructions to the lab staffs, which pushes me to think deeper about the experiments and how to achieve our goals through these experiments."*

The open-ended structure of the projects afforded students opportunities to feel a sense of agency in the class, through designing their own procedures and experiments, thinking independently about the experiments, and figuring out how to solve a problem that did not necessarily have a single correct or known solution, all things that students describe as being positive aspects contributing to their enjoyment of the course. In the interview, Mei described being able to explore things she was interested in within the structure provided by instructors, and being able to ask and answer her own questions. She said,

> *"I personally really enjoyed the process because…I felt like we were given more flexibility, like we weren't given specific instructions…instead of that we were given a topic [and] we were told we could like explore things we were interested in. We had like a general guideline, but I think we were able to pick, well it depends on the projects, but for one of the projects I felt like I was able to try to ask my own questions and try to move forward and try to answer my own questions and come up with ways to address the problem."*

Thus, the combination of structure and guidance provided by instructors with the flexibility for students to determine and pursue their own questions worked well for Mei. One other student in the open response dataset commented that the course had a "good balance between open-endedness and structure" (*good balance between open-ended and structure* code). This is aligned with research on student ownership that talks about the importance of striking a balance between instructor support and student control [27,35].

In the case of Mei, this opportunity for agency and balance between instructor guidance and freedom to explore also had positive impacts on her sense of identity as a physicist. At the time of the interview, Mei had been working in a high energy lab for two years and said the open-ended projects in the remote course, with opportunities to ask her own questions and explore what she was interested in, felt similar to actual research. She contrasted this with the prior in-person quarters in which they followed manuals and had to answer specific questions, an approach which she said laid a good foundation for the third quarter, but was not as fun as the open-ended projects that offered more flexibility. Mei explained that her experience engaging in the open-ended projects during the remote quarter impacted the way she plans to approach her research going forward. She said,

> *"I guess it gives me more confidence in doing my own research…after that process [of doing the projects in the spring quarter class] I felt more capable of coming up with my own questions and developing ways to solve the problems. Because before that [in my research group] I was mainly given a task and I was told to do this and do that and use code to fix this problem. I didn't have much independence. And I've always thought I would like more autonomy, but I also felt like is this task too difficult for me to come up with some solutions? But after spring quarter, first of all, I really enjoyed that process where I discovered a problem and I figured out ways to solve it and that also made me more confident in my ability to do this again in real research."*

Another way in which the structure of the course afforded opportunities for student agency was the longer time-frame of projects and flexibility of the asynchronous format. A majority of students agreed (or strongly agreed) that the remote lab was better than the in-person course at enabling them to work at their own pace (Table I). This is aligned with results we have seen from remote physics lab courses in general [1], and may simply be a result of the asynchronous, remote nature of the course. It may, however, also be due to the open-ended nature of the projects. Students had four weeks to complete each project, and a two-week period in which to submit data collection requests. Within that time, students had the freedom to make progress at their own pace and define their own schedule for working with their group. In some instances however, when individual group members'schedules and paces were not aligned, this freedom may have led to frustrating group work experiences, as we discuss in Sec. VI B below.

In addition to providing opportunities for student agency, for some students the projects allowed more meaningful social interactions. In the open-response dataset, one student commented that because of the open-ended nature of the project, they were able to "engage more meaningfully with my group members as well as the lab staff" (*allowed more meaningful interactions* code). We discuss this collaboration aspect further in the following section.

B. Collaboration

Students in our dataset had mixed experiences with collaboration in the remote course. Some students reported positive and meaningful group work experiences, while others cited the remote collaboration as a source of frustration or stress. In response to the statements that the remote course was better at enabling productive or enjoyable collaborations than the in-person course, student responses were roughly evenly distributed across disagree, neutral, and agree (Table I). This is consistent with the mix of experiences students shared with us in open-response questions and interviews, including developing skills for productive collaboration, experiencing group work as helpful or enjoyable, experiencing frustration with remote collaboration, and encountering challenges with unresponsive group members and unproductive collaboration.

In the open-response questions, two students recognized and commented on the fact that the remote course had an explicit emphasis on collaboration (*collaboration emphasized in course* code). While students had worked in groups in the in-person quarters, the nature of the collaboration was fundamentally different now that they had to determine their own experimental procedures, decide what data to collect, and solve a problem as a group. Samuel also commented on this in the interview, saying that the remote course was more group-oriented whereas the in-person version of the course had been more individual oriented. He explained that in the in-person course the purpose of group work was mainly to have multiple people working on the apparatus, but it was not necessarily collaborative because everyone just did their own individual final report. In contrast, he perceived group work to be a specific goal of the remote course. When asked what he thought students should take away from this course, Samuel talked about how one of the main goals of the course was to learn how to work in a research group, including communicating and collaborating with peers. He explains,

> *"The spring was much more like, this is how potentially working in a research group might be like…you need to request data, you have to communicate in a group, you have to divide work, etc. And so it felt like the spring was much more focused on like providing you a simulacrum of what working in a research group is like, and helping you learn about these ideas and these structures and how you can operate in that space."*

Similar to Samuel, other students also recognized that productive collaboration is an important skill to learn. In her interview, Amy mentioned that remote collaboration is a realistic practice of scientists (e.g., working with large international collaborations) and commented that it was a good thing to learn and practice in this course. Two other students in the open responses said that this course helped them learn important skills for productive collaboration (*learned how to collaborate productively* code). For example, one student wrote,

> *"One of the skills that I learned is how to work with a group on a project and making sure every member does his/her part so that the group can move forward. It takes some honest, transparent and proactive conversations/approaches, which I have learned to develop somehow in this term."*

In the closed-response data, roughly a third of respondents said that the remote course was better at enabling them to have enjoyable or productive collaborations. In the open-response data, two students wrote about collaboration as being a helpful or enjoyable aspect of the course (*collaboration was helpful or enjoyable* code). One of those students was Samuel, who in response to the question about how the remote course impacted his learning said, "I had more discussion with my group mates and hearing their thoughts and ideas was helpful for understanding complex issues." In the interview, he reiterated that he personally had a positive group work experience, though he did hear stories from friends in the course who did not have such positive experiences with their groups.

Samuel explained that while his group work experience was positive, the main difficulty he encountered with remote collaboration was scheduling group meetings across multiple time zones. Several other students made similar comments in the open-response questions. The *missed in-person interaction* code, applied to seven students, encompasses statements about how remote collaboration was challenging (e.g., coordinating across time zones) or not as good as in-person interaction. This code does not necessarily mean that students had negative group work experiences, just that remote collaboration was more difficult or less enjoyable than in-person collaborations would have been. The two main things that students said they missed about the in-person lab course were face-to-face interactions with people and working in the lab with physical equipment (the latter is discussed in Sec. VI C).

Beyond the challenges of adapting to remote collaboration and not having access to peers and instructors in person, five students described negative group work experiences (*negative group work experience* code). Some students generally reported that the biggest challenge of the course was dealing with their group members, e.g., because they were unresponsive. One student mentioned unequal division of work and low accountability: "I also think that our first group did not divide work equally. Our second round did better, but I still felt like there was a low accountability for group participation." In the interview, Amy also described variation between groups. She said her first group was "fine," but the second group was unresponsive, which led to her doing most of the work. Thus, she characterized her experience with remote collaboration overall as frustrating. Amy explained that the group work would probably have been less frustrating if they had been able to select their own groups, though she did appreciate being able to meet and work with new people.

Some students explicitly acknowledged the stressful pandemic circumstances in which they were working, and spoke to how that impacted or aggravated the challenges they faced with remote collaboration. One student wrote,

> *"Working with groupmates remotely can be quite hard sometimes because when it comes to data analysis, we divided the work among all of us. So, when someone doesn't do his/her work, this affects the group's ability to move forward to do other things. It is understandable that it is a hard time for everybody (e.g., pandemic, other courses'workload), so it was also hard to push a groupmate to complete her part quickly. Thus, it could be quite an uncomfortable situation when a group member is falling behind. This didn't happen in previous in-lab courses because every individual does his/her own data analysis."*

Collaborative situations that require students to depend on one another, such as that presented by the open-ended projects, can lead to tensions between dependence and independence among individual group members, hampering productive group work [36]. In some groups, these tensions may have been exacerbated by the remote modality and the challenging circumstances students were experiencing.

Overall in the dataset, we see a range of experiences around group work and collaboration. Consistent with this variation, in the interview Mei described having "drastically different experiences" between her two projects. She said her first group worked well together, and as a result she enjoyed the first project—one group member was especially organized, the group divided up the work equally, they were excited to share results with each other, and in general they did not encounter any problems. In contrast, her second group worked more individually, and the project was not as collaborative or fun. Mei explains that this was likely due to the nature of the particular project. Compared to the first project, she said that for the second one the instructors provided more instructions and indicated how the work should be broken up into three distinct parts. As a result, each group member worked individually on one part of the project and there was not much opportunity for meaningful or positive collaboration. We find that there was large variation in students' remote collaboration experiences depending on the individuals in the group, the specific project, and the extenuating circumstances of the pandemic and how that was impacting various individuals.

C. No hands-on work

In both the open responses and interviews, some students said they did not necessarily miss anything about the in-person course and preferred the model with the more open-ended projects to the traditional lab format. However, the most common thing that students said they did miss was the ability to be in the lab working hands-on with equipment. In response to the open-response question about what they missed about the in-person course, seven students talked about missing being able to work with equipment, collect data, or conduct the experiment themselves (*missed working with equipment* code). One student explained that not being in the lab in-person made it harder to understand aspects of the experiment, like how the apparatus works or how to take measurements (*harder to understand experiments* code).

This result is in line with what we expected given the circumstances of the rapid transition to remote teaching and learning. In an initial study of remote physics lab courses in Spring 2020, we found that having hands-on work similar to a normal mode of operation in an in-person lab course was a common motivation for lab instructors, and was one of the biggest challenges that both instructors and students reported facing [1]. While many introductory lab courses found ways to incorporate hands-on activities by having students use materials from home or sending them lab kits, it was more difficult to do so in a short amount of time for advanced lab courses that require more advanced apparatus.

On the closed-form survey questions, 78% of students disagreed or strongly disagreed that the remote course was better at helping them learn laboratory skills, while only 9% agreed. That is, students did not feel like they learned laboratory skills as much in the remote version of the course as they had in the prior in-person quarters. In contrast, Joel reported on the instructor survey that, in the transition from in-person to remote teaching, the goals of the course shifted from a combination of developing lab skills and reinforcing physics concepts to primarily focus on developing lab skills. Although it is possible that the instructor's goal of developing lab skills was not achieved in the remote version of the lab, another explanation for the inconsistency between the students' perspective and the instructor's may be that students consider "laboratory skills" to mean working hands-on with apparatus. They reported that, in the remote version of the course, they were not offered the opportunity to practice setting up, troubleshooting, or working with physical equipment. To an expert, laboratory skills often encompass a wide range of things like experimental design, modeling, collaborating, etc., which students may not consider as lab skills.

Not all students missed working with equipment in-person. In the interviews, Mei and Amy both explicitly said they did *not* miss working with equipment in the lab. Amy actually described this shift as a welcome change because she "despises troubleshooting" and was happy to have someone else collect data for her that she could then work with.

D. Workload and stress

Across all three data sources (closed-responses, open-responses, and interviews), students' reactions to the new format of open-ended projects was overwhelmingly positive. However, for some, despite the benefits of the open-ended structure of projects, they also presented additional challenges because there was a high workload and the expectations were not always clear.

The fourth main theme that emerged from the data analysis only has one code: *workload and stress*. Though many students enjoyed the remote lab course, some also said the workload was overwhelming, which made the course stressful. This workload and stress code applies to students who talked about the course as being overwhelming, too much work, or stressful. In this vein, some students also mentioned that the expectations for the course were unclear, which contributed to the stress and the overwhelming workload. This code was applied to five students' responses in the open-response dataset. Students described the workload as being overwhelming because there were sometimes multiple assignments due at once (e.g., the first project report and a first draft of the journal article) or because they were unclear about what they needed to do and when.

In response to the statement that the remote lab course was better at providing clear expectations than the in-person course, 54% of respondents disagreed or strongly disagreed and 41% responded neutrally. This result is aligned with results we see from remote lab courses in general in Spring 2020 [1]. As evidenced in the students' open responses, these unclear expectations were in part resulting from the fact that the students had never done open-ended projects like this before. One student wrote, "since the projects and work we were submitting were so different from the in-person portion, knowing the expectations was difficult." Even in an in-person course, we might expect that making this switch from traditional prescriptive labs one quarter to more open-ended projects the next quarter would result in confusion or uncertainty among students in terms of the expectations for course work. In fact, some instructors have previously reported employing metacognitive activities in an in-person advanced lab course in order to help students transition to open-ended lab work and to normalize the frustrations of conducting such open-ended projects [37]. Additionally, the unclear expectations reported by students in this course were likely also a result of the chaos of quickly transitioning to remote teaching. With only a couple weeks to prepare for the course, instructors were required to learn and adapt in-the-moment.

In response to the open-response question about how the remote lab instruction impacted their learning, Amy wrote,

> *"The class was, on the whole, extremely stressful and an enormous time commitment; I enjoyed the material covered and the projects themselves, but in addition to all of my other schoolwork, the workload was overwhelming."*

She expanded on this in the interview and said that the first half of the course was rough, but that it gradually got better because instructors asked for feedback on a mid-term survey and tried to adjust in response to students' concerns and challenges. This fits with the instructor perspective of the course as well, discussed in the following section.

Both instructors and students were navigating the new territory of what it means to teach and learn remotely, in addition to the new open-ended structure of projects. In addition to the stresses and trauma from the global pandemic, this resulted in some students feeling stressed and overwhelmed with their coursework. Instructors were attentive to this situation and lenient in their grading, which at least some students noticed and appreciated. In the interview, Mei said that the instructors were understanding and let the students submit work late, which she appreciated.

VII. ADDITIONAL OUTCOMES

One way to assess the impact of a lab course is to look at how students' views about experimental physics change by looking at the pre-post shifts in students' E-CLASS scores. Instructors who administer the E-CLASS in their course typically do so as a way to assess, and improve upon, their lab courses. The course in our case study has administered the E-CLASS for many years, and they do so with the presurvey given at the beginning of the fall quarter and the post-survey given at the end of the spring quarter (rather than a pre- and postsurvey each quarter). Thus, any shifts in E-CLASS scores from pre to post represent shifts in students' attitudes about experimental physics over the course of the year-long advanced lab sequence. In the 2019–2020 academic year, the mean prescore was 16.81 (SE $= 1.50$), on a scale of -30 to 30, and the mean post-score was 20.63 (SE $= 1.31$). This pre-post shift is not statistically significantly different than that in the prior two years. Using the Mann-Whitney U test to compare the pre-post shift in the 2019–2020 academic year to the 2018–2019 and 2017–2018 academic years, we find $p = 0.86$, $r = -0.02$ and $p = 0.34$, $r = -0.16$, respectively, and for both effect sizes the 95% confidence interval overlaps with zero. Thus, we conclude that the shift in E-CLASS score in 2019–2020 was no different than in prior years, noting that the sample sizes are small. This is contrary to past work which has suggested that open-ended labs serve to increase E-CLASS score compared to traditional, guided laboratory activities [38]. However, since two thirds of the coursework in that time was the traditional in-person format and only one third was the new remote format with open-ended projects, we might not expect to detect any differences in students' views due to the open-ended projects in the total E-CLASS score, because it takes time and reflection for students' epistemologies to develop [39]. It is, however, encouraging that the scores did not significantly decline after the remote quarter. This aligns with results we have reported for a sample of introductory lab courses during the pandemic [4].

Of the four main course goals (see Sec. V), only one of them is specifically addressed by an E-CLASS item. The course goal of moving away from the mindset of trying to attain a particular result lines up with the item 'The primary purpose of doing a physics experiment is to confirm previously known results' (with an expertlike response of disagree.) In the 2019–2020 academic year, students in this course shifted to be more expertlike on this item, from 48% of students aligned with the expertlike response on the presurvey to 67% on the postsurvey. This differs from the prior two years of the course in which there was no shift or a slight downward shift on this item (it remained at 55% in 2017–2018 and shifted from 77% down to 73% 2018–2019). This positive result highlights the benefits of the open-ended structure of projects even in an emergency remote teaching situation, and is directly aligned with one of the major course goals and with the lab work that students engaged in (i.e., in the projects they conducted there was no particular answer or result they were looking to confirm). A similar result on this one E-CLASS item has also been seen across multiple introductory lab courses during the pandemic [4].

VIII. INSTRUCTOR PERSPECTIVES

In addition to documenting students' experiences in the course and looking at E-CLASS results, we can understand the remote lab course by investigating the instructor's perspective on successes and challenges that they faced. On the instructor survey, Joel reported a high level of student engagement in the course and cited this as a measure of success for the course. He wrote,

> *"The level of student engagement was much higher in the remote format. Students were much more engaged in problem solving and making meaningful decisions about what to do and how to do it."*

In the interview, he expanded on this perception and attributed the high level of engagement to the open-ended structure of the projects. He said that it was clear that students were more invested in the course because they were thinking about the experiments and choosing what to do, whereas in the traditional in-person format, students just wanted to get the right answer so they could leave the lab to work on other coursework. Joel observed that, compared to the traditional labs, with the open-ended projects, students were more satisfied when something worked and when something did not work they were invested in trying to figure it out. This is aligned with Samuel's experience as he described the open-ended projects as being more engaging (discussed in Sec. VI A). Additionally, Joel said that interactions between instructors and students were "much more like a partnership on a project," where conversations were more meaningful instead of the typical in-person conversations about clarifying instructions in a lab manual or helping students get a signal on an oscilloscope. He said that students seemed to respond to this structure much better, and were invested in pursuing their own ideas.

Although the implementation of the new open-ended projects was very successful, there were, of course, challenges that the instructors had to overcome in order to achieve such high level of student engagement. In general, there were many challenges that physics lab instructors across the country faced in the transition to remote teaching [1], including technological constraints and students not having access to experimental apparatus. Joel described these challenges, and said with more preparation time they could have set up some of the experiments for students to control remotely, rather than needing to rely on instructors going in to the lab and collect data. Beyond these issues, Joel wrote on the survey,

> *"The biggest challenge was the inability to test our ideas before hand. We had to do a lot of evaluation and modification in the first few weeks as we saw what worked well and what didn't."*

In Secs. VI B and VI D above, we presented experiences that students shared around being overwhelmed and unclear about course expectations or having unproductive group work situations. The instructors heard these concerns during the course and tried to make appropriate modifications. In the interview, Joel said that he felt bad because the instructors had misjudged the time required to complete coursework and students ended up having more work than they had intended. Though from his interactions with students, Joel got the sense that the students were not too upset about the workload because the course overall was more intellectually stimulating than the prior quarters. This situation of an unintended high workload is aligned with recent research on students' experiences in synchronous versus asynchronous remote physics courses in which students who participated asynchronously reported needing to spend more time on coursework [40].

The major modification the instructors made to the course structure between the first and second projects was around the collaboration aspect. Whereas in the first project, they left it completely up to students to schedule meetings with one another and with instructors, for the second project, weekly group meetings were required and more structured. Groups would meet with a TA and instructor and each individual student was expected to provide an update on what they had worked on that week, akin to weekly group meetings that might take place in a research group. This additional structure around group meetings was intended to help mitigate some of the issues students were experiencing with frustrating or unproductive group work situations.

A testament to the success of this new remote version of the course, Joel reports that the instructional team plans to continue the open-ended projects in future remote and in-person implementations of the course. On the survey he wrote,

> *"For our institution the positives of what we tried out weighed the negatives. While we would not choose to run the course in the [remote] manner we did, future iterations of the course are likely to more closely resemble what we did this quarter than how they were previously done."*

Thus, in this case, the transition to emergency remote teaching facilitated a larger scale and possibly longer-term transformation of the underlying goals and structure of the advanced lab course.

We conducted the instructor interview immediately after the completion of the spring quarter. At this time, Joel explained that they were faced with the challenge of how to implement the course in the Fall 2020 quarter, which would again be taught remotely. He described that a major benefit for the spring remote quarter was that students had all completed two quarters of the in-person course, thus gaining experience and familiarity with the experiments and equipment. Because each student had conducted a handful of the experiments in-person and was familiar with the equipment, they were able to jump into the remote projects, using what they knew about the equipment to request data for the instructors to collect. At least one student also noted the benefit of having in-person experience prior to the remote course. As part of their answer about their favorite aspect of the course, they wrote,

> *"I think I got a lot out of taking one quarter of a "complete this collection of tasks" lab class, but the second quarter felt repetitive, and I don't believe the second quarter of [the course] helped me to better communicate ideas or conduct experiments. I think the remote quarter was a refreshing change of pace."*

At the time we interviewed Joel, he was not yet sure how they were going to accomplish something similar with the first quarter of the year-long series being remote, though he viewed it as a challenge that he and the other instructors were excited to tackle.

In a subsequent round of data collection as part of an ongoing study, we administered another instructor survey after the Fall 2020 term. One of the instructors from this course responded and provided an update as to how they ended up running the course. In the Fall 2020 quarter, the class was again entirely remote and operated in a similar manner to the Spring 2020 quarter described in this paper. Students worked in groups of three on two four-week-long projects; they used a Wiki page to collaborate on the projects and each student wrote an individual report at the end of the project. For the first project, all students in the course conducted the gamma cross-section experiment, using a remote-access system to remotely operate the physical apparatus in the lab. This setup allowed students full control over the data collection process, rather than having to submit data collection requests to instructors. For the second project, groups did different experiments; most of these projects involved having instructors go into the lab to collect data that the students requested (just like in the spring quarter), though one of the experiments did have a remote access set up. In addition to the projects, students participated in a journal club and answered questions about, or wrote a summary of, scientific papers. On the Fall 2020 survey, the instructor reported that going forward when courses return to an in-person modality they will likely keep the longer timescale and more open-ended projects. Additionally, they suggested that they may also maintain the remote access option for some of the experiments so that students can collect data from home outside of class time in addition to physically collecting data in the lab.

Since this paper focuses on an analysis of the Spring 2020 implementation of the remote course, we do not have further information from the instructors on successes and challenges of the Fall 2020 remote quarter, nor do we have data from students on their experiences in this course. It would be interesting to follow up with both instructors and students to see how the course, students' learning, and students' experiences continue to evolve as the new course goals and structure are refined for future in-person implementations.

IX. IMPLICATIONS

The students' experiences in this course that we have documented here provide implications for in-person and remote lab courses in the future: open-ended projects can be beneficial and more enjoyable for students even when not fully student-designed and even in a remote format, it is possible to conduct some aspects of advanced labs remotely, implementing successful group work may require intentional and consistent attention, and it can be helpful for instructors to make course goals and expectations clear for students.

This case study demonstrates some of the possible benefits of open-ended projects that provide opportunities for students to think critically and make decisions about their experiments. Courses that focus on these types of projects can be more enjoyable for students, beneficial for students' learning about the process of experimental physics, and can lead to high student engagement. Though the benefits of open-ended lab activities and student projects are well documented in the literature [21–29], this case study demonstrates that even in a chaotic and less than ideal emergency remote teaching context, students can gain tremendous benefit from engaging in open-ended projects.

There are a variety of ways to implement such open-ended projects, in any lab course at any level. A common format in advanced lab courses is to have multiweek projects that are student-designed from beginning to end. However, the course in this case study demonstrates that advanced lab projects do not necessarily need to be fully student-designed in order to be beneficial for students. In this example, the instructors defined the overall project topics and goals and provided guidance along the way. Within that structure, students could explore their own paths, think independently, and make decisions about their experiments. In fact, one advantage to this type of guided yet open-ended project is striking a balance between the amount of agency students have and the amount of instructor support they receive [35]. Further, instructors of advanced lab courses may consider first providing students with guidance on how to use a particular apparatus (like students in this course received in the first two in-person quarters) and then removing that scaffolding and allowing students more freedom to explore and design their own experiments or procedures using the same apparatus.

This case study also demonstrates that lab courses that use advanced apparatus *can* be conducted remotely. Though not ideal in the remote format, there were still many benefits to students. With more time and advanced planning, it is feasible to set up labs such that students can remotely operate the equipment, as the instructors in our case were able to do for the Fall 2020 remote course. This has implications for expanding access to advanced physics lab courses, for students who are not able to attend in-person courses or who would benefit from being able to collect data outside of regular class and lab hours.

This study also provides implications for group work in both remote and in-person lab courses. Group work plays a central role in many lab courses, and helping students develop collaboration skills is often an explicit goal of physics lab instruction [11,15]. Courses that feature collaborative open-ended projects present unique opportunities for students to develop these skills and experience the collaborative nature of experimental physics. The student experiences presented in this case study show that it is *possible* for students to have productive and enjoyable collaborative experiences, specifically around open-ended projects, but it is not a given and we may need to attend to the group work dynamics throughout the duration of the course to ensure all students are having this positive experience [41,42].

Although group work comes with many benefits and is recognized as important for developing vital skills within physics and across many disciplines [11,19,43,44], it can also be a major source of conflict for students due to a variety of factors such as perceptions that not all members are working at equal levels or are equally committed to the process (social loafing) [45–48] or difficulty with working across differences among group members [47,48]. Remote group work can often further compound these difficulties [46,47]. Literature on group work in physics labs specifically suggests that we focus on promoting equitable collaborations by attending to division of labor (in terms of both amount of work and type of work each group member does), gendered roles, and making sure every student's bids are heard by their peers [49–51]. Instructors might also consider the benefits and disadvantages of assigning groups versus allowing students to self-assemble [52,53].

In this course, at least some students picked up on the explicit foci on experimental design and collaboration in a way that felt different from their prior in-person labs, and they said they got this messaging directly from the instructors and the way the course was structured. Explicit framing and discussion around the goals and purpose of group work in a course may help students learn about the collaborative nature of experimental physics, get in the mindset for conducting experiments that do not necessarily have a right answer or method, and have accurate expectations for the course.

X. CONCLUSIONS

We conducted a case study analysis of one advanced lab course that transitioned from traditional prescriptive labs to more open-ended four-week-long projects simultaneously with the transition to remote teaching due to the COVID-19 pandemic. Triangulating across multiple data sources—instructor survey responses, instructor interview, E-CLASS results, student closed- and open-responses to remote lab survey questions, and student interviews—we constructed an in-depth understanding of the course (context, goals, structure), students' experiences with the open-ended projects in the remote format, and the instructor's perspectives on successes and challenges. We identified four major themes in our analysis: open-ended structure of projects, collaboration, no hands-on work, and workload and stress.

From the students in our dataset, there was an overwhelmingly positive response about the open-ended nature of projects. Although we cannot necessarily generalize the results of this analysis to the entire student experience in the course (out of a total enrollment of 60 students, we had 3 student interviews, 22 closed responses to the remote lab survey questions, and 16 open responses), for these students, the open-ended structure afforded them opportunities to ask questions they were interested in, design their own procedures, and think deeply about their experiments. The instructor credits these opportunities for student agency for the high student engagement observed in the course, a result that is particularly impressive given the emergency remote teaching context.

Students' experiences with remote collaboration were mixed. Some students had meaningful and positive collaborations with their groups and felt that the course helped them learn important skills related to collaboration, while other students had negative group work experiences that were a source of frustration and stress. In between those two extremes, many students commented on the ways in which remote collaboration was more difficult than in-person collaboration (e.g., coordinating meetings across time zones).

The main thing that these students missed about the in-person course was being able to be in the lab and work hands-on with equipment. While students were able to design their own procedures, experiments, and analysis methods and complete a project using advanced apparatus by submitting data collection requests to instructors, they were not able to physically work with, and troubleshoot, the equipment.

Some students said the workload was too high and the expectations for the course were unclear, which made the course overwhelming and stressful. We believe this was the result of both the rapid transition to emergency remote teaching, as well as the transition from traditional prescriptive labs to more open-ended projects. The instructors attempted to correct for this in response to students' concerns and feedback midway through the term. This solicitation of, and acting on, feedback was appreciated by students and is particularly important when implementing major changes to a course.

This case study analysis demonstrates some of the possible benefits of open-ended projects in physics lab courses, even in a remote format, and offers an example of how to implement projects in an advanced lab course that balance instructor direction and guidance with opportunities for student agency. The lessons learned from the first implementation of this new version of the course may be instructive for both in-person and remote lab courses.

ACKNOWLEDGMENTS

We thank the instructor and students who shared their experiences with us, especially during such a challenging time. This work is supported by NSF Grants No. DUE 1726045, No. DUE 2027582, and No. PHY 1734006. Viewpoints expressed here are those of the authors and do not reflect views of NSF.

APPENDIX

Table II shows the results of the coding analysis of the open-response student survey questions.

TABLE II. Emergent codes from the analysis of students' responses to open-response survey questions about the remote lab course. The 13 codes are categorized into four main themes: open-ended structure of projects, collaboration, no hands-on work, and workload and stress. N is the number of students who had at least one response coded with a given code (out of 16 students who answered some or all of the open-response questions).

Code	Definition	N
Open-ended structure of projects		
Liked experimental design	Student talks about designing experiments, or aspects of experimental design (including choosing what data to collect), as a positive experience or thing they liked about the course.	10
Experimental design emphasized in course	Student recognizes and explicitly state that experimental design was an emphasis of the remote course.	2
Critical thinking required	Open-ended structure required students to engage in "critical thinking," "independent thinking," or "problem solving." This code applies when students use any of these phrases or talk about having to think deeply about their experiments.	4
Good balance between open-ended and structure	Student states that there was a good balance between the open-ended and guided aspects of the course.	1
Allowed more meaningful interactions	Student reports that the open-ended nature of projects allowed them to have more meaningful interactions with group members/instructors.	1
Collaboration		
Collaboration emphasized in course	Student recognizes and explicitly state that collaboration/group work was an emphasis of the remote course.	2
Learned how to collaborate productively	Student states that the course helped them develop collaboration/group work skills. E.g., communicating with group members, ensuring everyone does their work, collaborating with a large team.	2
Collaboration was helpful or enjoyable	Student describes collaboration as helpful (to their learning, their experiments, etc.) or as something they liked.	2
Missed in-person interaction	Student states that they missed in-person interactions, would have preferred in-person interactions, or that remote collaboration was challenging (e.g., coordinating across time zones). The response does not directly indicate a bad group work experience, but rather a challenge or inconvenience. Though some students may have stated both that they missed in-person interaction and that they had a negative group work experience (see next code).	7
Negative group work experience	Student describes or implies a bad group work experience (e.g., "the biggest challenge was my group members," "having unresponsive group members was bad for my learning," or "we didn't divide the work equally").	5
No hands-on work		
Missed working with equipment	Student talks about missing being in lab, working with equipment, collecting data, or conducting the experiment themselves.	7
Harder to understand experiments	Not being physically in the lab made it harder to understand aspects of the experiment (e.g., the apparatus, how to make measurements).	1
Workload and stress	Student describes the course as being overwhelming, stressful, or too much work. They might also state that the expectations for the course were unclear (because everything was new or the timelines/requirements were not communicated clearly), thus contributing to the high workload or stressful experience.	5

[1] M. F. J. Fox, A. Werth, J. R. Hoehn, and H. J. Lewandowski, Teaching labs during a pandemic: Lessons from Spring 2020 and an outlook for the future, arXiv:2007.01271.

[2] T. Feder, Universities overcome bumps in transition to online teaching, Phys. Today **73**, No. 6, 22 (2020).

[3] A. Werth, J. R. Hoehn, K. Oliver, M. F. J. Fox, and H. J. Lewandowski, Rapid transition to remote instruction of physics labs during Spring 2020: Instructor perspectives, Phys. Rev. Phys. Educ. Res. (in preparation).

[4] M. F. J. Fox, J. R. Hoehn, A. Werth, and H. J. Lewandowski, Lab instruction during the COVID-19 pandemic: Effects on student views about experimental physics in comparison with previous years, Phys. Rev. Phys. Educ. Res. **17**, 010148 (2021).

[5] P. Klein, L. Ivanjek, M. N. Dahlkemper, K. Jeličić, M.-A. Geyer, S. Küchemann, and A. Susac, Studying physics during the COVID-19 pandemic: Student assessments of learning achievement, perceived effectiveness of online recitations, and online laboratories, Phys. Rev. Phys. Educ. Res. **17**, 010117 (2021).

[6] S. Shivam and K. Wagoner, How well do remote labs work? A case study at Princeton University, arXiv:2008.04499.

[7] F. R. Bradbury and C. F. J. Pols, A pandemic-resilient open-inquiry physical science lab course which leverages the Maker movement, Electron. J. Res. Sci. Math. Educ. **24**, 60 (2020).

[8] F. Pols, A physics lab course in times of COVID-19, Electron. J. Res. Sci. Math. Educ. **24**, 172 (2020).

[9] D. Howard and M. Meier, Meeting laboratory course learning goals remotely via custom home experiment kits, arXiv:2007.05390.

[10] B. M. Zwickl, T. Hirokawa, N. D. Finkelstein, and H. J. Lewandowski, Epistemology and expectations survey about experimental physics: Development and initial results, Phys. Rev. ST Phys. Educ. Res. **10**, 010120 (2014).

[11] J. Kozminski, H. J. Lewandowski, N. Beverly, S. Lindaas, D. Deardorff, A. Reagan, R. Dietz, R. Tagg, M. Eblen-Zayas, J. Williams, R. Hobbs, and B. Zwickl, *AAPT recommendations for the undergraduate physics laboratory curriculum subcommittee membership*, Tech. Rep. (American Association of Physics Teachers Committee on Laboratories, College Park, MD, 2014).

[12] A. Sithole, E. T. Chiyaka, F. Manyanga, and D. M. Mupinga, Emerging and persistent issues in the delivery of asynchronous non-traditional undergraduate physics experiments, Int. J. Phys. Chem. Educ. **12**, 1 (2020).

[13] C. Colwell, E. Scanlon, and M. Cooper, Using remote laboratories to extend access to science and engineering, Comput. Educ. **38**, 65 (2002).

[14] D. J. Rosen and A. M. Kelly, Epistemology, socialization, help seeking, and gender-based views in in-person and online, hands-on undergraduate physics laboratories, Phys. Rev. Phys. Educ. Res. **16**, 020116 (2020).

[15] L. Leblond and M. Hicks, Designing laboratories for online instruction using the iolab device, Phys. Teach. **59**, 351 (2021).

[16] J. Ma and J. V. Nickerson, Hands-on, simulated, and remote laboratories: A comparative literature review, ACM Comput. Surv. **38**, 7 (2006).

[17] B. Wilcox and M. Vignal, Recommendations for emergency remote teaching based on the student experience, Phys. Teach. **58**, 374 (2020).

[18] T. Feder, College-level project-based learning gains popularity, Phys. Today **70**, No. 6, 28 (2017).

[19] Joint Task Force on Undergraduate Physics Programs, *Phys21: Preparing physics students for 21st-century careers*, Tech. Rep. (American Physical Society and American Association of Physics Teachers, College Park, MD, 2016).

[20] J. R. Hoehn and H. J. Lewandowski, Framework of goals for writing in physics lab classes, Phys. Rev. Phys. Educ. Res. **16**, 010125 (2020).

[21] J. R. Hoehn and H. J. Lewandowski, Incorporating writing in advanced lab projects: A multiple case-study analysis, Phys. Rev. Phys. Educ. Res. **16**, 020161 (2020).

[22] N. G. Holmes, B. Keep, and C. E. Wieman, Developing scientific decision making by structuring and supporting student agency, Phys. Rev. Phys. Educ. Res. **16**, 010109 (2020).

[23] P. W. Irving and E. C. Sayre, Conditions for building a community of practice in an advanced physics laboratory, Phys. Rev. ST Phys. Educ. Res. **10**, 010109 (2014).

[24] D. R. Dounas-Frazer, K. S. Johnson, S. E. Park, J. T. Stanley, and H. J. Lewandowski, Student perceptions of laboratory classroom activities and experimental physics practice, in *Proceedings of the 2020 Physics Education Research Conference*, virtual conference, edited by S. Wolf, M. B. Bennett, and B. W. Frank (AIP, New York, 2020).

[25] N. M. Juma, E. Gire, K. Corwin, B. Washburn, and N. S. Rebello, Students' and instructor's impressions of ill-structured capstone projects in an advanced electronics lab, AIP Conf. Proc. **1289**, 181 (2010).

[26] M. Martinuk, R. Moll, and A. Kotlicki, Research projects in introductory physics: Impacts on student learning, AIP Conf. Proc. **1179**, 193 (2009).

[27] D. R. Dounas-Frazer, J. T. Stanley, and H. J. Lewandowski, Student ownership of projects in an upper-division optics laboratory course: A multiple case study of successful experiences, Phys. Rev. Phys. Educ. Res. **13**, 020136 (2017).

[28] D. R. Dounas-Frazer and H. J. Lewandowski, Correlating students' views about experimental physics with their sense of project ownership, in *Proceedings of the 2018 Physics Education Research Conference, Washington, DC* (AIP, New York, 2019).

[29] D. R. Dounas-Frazer, L. Ríos, and H. J. Lewandowski, Preliminary model for student ownership of projects, in *Proceedings of the 2019 Physics Education Research Conference, Provo, UT* (AIP, New York, 2019).

[30] J. Arnold and D. J. Clarke, What is 'Agency'? Perspectives in science education research, Int. J. Sci. Educ. **36**, 735 (2014).

[31] PhET Interactive Simulations, https://phet.colorado.edu/ (2021).

[32] B. Gregorcic and M. Bodin, Algodoo: A tool for encouraging creativity in physics teaching and learning, Phys. Teacher **55**, 25 (2017).

[33] S. B. Merriam, The case study in educational research: A review of selected literature, J. Educ. Thought **19**, 204 (1985).

[34] H. J. Lewandowski, D. R. Bolton, and B. Pollard, Initial impacts of the transformation of a large introductory lab course focused on developing experimental skills and expert epistemology, in *Proceedings of the 2018 Physics Education Research Conference, Washington, DC*(AIP, New York, 2018).
[35] D. I. Hanauer, J. Frederick, B. Fotinakes, and S. A. Strobel, Linguistic analysis of project ownership for undergraduate research experiences, CBE Life Sci. Educ. **11**, 378 (2012).
[36] K. K. Smith and D. N. Berg, *Paradoxes of Group Life: Understanding Conflict, Paralysis, and Movement in Group Dynamics* (Jossey-Bass, San Francisco, CA, 1987).
[37] M. Eblen-Zayas, The impact of metacognitive activities on student attitudes towards experimental physics, in *Proceedings of the 2016 Physics Education Research Conference, Sacramento, CA* (AIP, New York, 2016).
[38] B. R. Wilcox and H. J. Lewandowski, Open-ended versus guided laboratory activities: Impact on students' beliefs about experimental physics, Phys. Rev. Phys. Educ. Res. **12**, 020132 (2016).
[39] W. Sandoval, Science education's need for a theory of epistemological development, Sci. Educ. **98**, 383 (2014).
[40] S. Guo, Synchronous versus asynchronous online teaching of physics during the COVID-19 pandemic, Phys. Educ. **55**, 065007 (2020).
[41] S. L. Eddy, S. E. Brownell, P. Thummaphan, M.-C. Lan, and M. P. Wenderoth, Caution, student experience may vary: Social identities impact a student's experience in peer discussions, CBE Life Sci. Educ. **14**, ar45 (2015).
[42] K. L. Tonso, Teams that work: Campus culture, engineer identity, and social interactions, J. Eng. Educ. **95**, 25 (2006).
[43] R. Lingard and S. Barkataki, Teaching teamwork in engineering and computer science, in *Proceedings of the Frontiers in Education Conference, FIE* (IEEE, New York, 2011).
[44] S. M. Goltz, A. B. Hietapelto, R. W. Reinsch, and S. K. Tyrell, Teaching teamwork and problem solving concurrently, J. Management Educ. **32**, 541 (2008).
[45] S. J. Karau and K. D. Williams, Social loafing: A meta-analytic review and theoretical integration, J. Personality Social Psychol. **65**, 681 (1993).
[46] M. C. Yang and Y. Jin, An examination of team effectiveness in distributed and co-located engineering teams, Int. J. Eng. Educ. **24**, 400 (2008).
[47] M. Borrego, J. Karlin, L. D. Mcnair, and K. Beddoes, Team effectiveness theory from industrial and organizational psychology applied to engineering student project teams: A research review, J. Eng. Educ. **102**, 472 (2013).
[48] J. M. Dirkx and R. O. Smith, Thinking out of a bowl of spaghetti, *Online Collaborative Learning* (IGI Global, Pennsylvania, USA, 2004), pp. 132–159.
[49] D. Doucette, R. Clark, and C. Singh, Hermione and the secretary: How gendered task division in introductory physics labs can disrupt equitable learning, Eur. J. Phys. **41**, 035702 (2020).
[50] D. Doucette, R. Clark, and C. Singh, What makes a good physics lab partner?, in *Proceedings of the 2020 Physics Education Research Conference*, virtual conference (AIP, New York, 2020), pp. 124–130.
[51] S. M. Jeon, Z. Y. Kalender, E. C. Sayre, and N. G. Holmes, How do gender and inchargeness interact to affect equity in lab group interactions?, in *Proceedings of the 2020 Physics Education Research Conference*, virtual conference (AIP, New York, 2020), pp. 240–245.
[52] K. M. Cooper and S. E. Brownell, Coming out in class: Challenges and benefits of active learning in a biology classroom for LGBTQIA students, CBE Life Sci. Educ. **15**, ar37 (2016).
[53] S. Hilton and F. Phillips, Instructor-assigned and student-selected groups: A view from inside, Issues Accounting Educ. **25**, 15 (2010).