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Self-guided Inquiry Modules for the Remote Teaching of Undergraduate Physics Labs

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Abstract

We present highlights from a series of hands-on physics lab modules developed for remote teaching. The labs were composed of multiple self-guided inquiry modules. Though the labs were developed from scratch, some modules that were central to the design process were borrowed from previous PDP sessions and the guiding PDP principles of mirroring authentic Science, Technology, Engineering, and Mathematics (STEM) practices (e.g., allowing students to raise questions and take ownership of decision making). One notable aspect of this work is that by sourcing and assembling low-cost ($25 per student) lab kits that were sent to each student, the majority of the modules were hands-on despite being fully online. Combining online resources and simulation tools with individual hardware kits and small lab groups allowed for a mix of synchronous and asynchronous exploration. This mixed lab mode was successful in promoting both inquiry exploration and community building. One example of a lab design choice aimed at overcoming online barriers was that in lieu of weekly lab write-ups, groups submitted video checkouts in which students were encouraged to reflect on the lab, self-assess their learning outcomes, and highlight unique aspects of their lab experience. This lab was specifically developed in response to the unforeseen challenges of online teaching; however, multiple aspects of the course will seamlessly transfer to an in-person lab setting.

Keywords: course design, inquiry, online/remote learning, physics

1. Introduction

The abrupt shift to online learning due to COVID-19 introduced pedagogical challenges across all fields, but laboratory classes in particular were especially impacted. Various approaches to addressing these challenges ranged from cancelling or postponing entire lab courses during the pandemic; relying on online materials such as simulators or canned data; and sending materials to students for both asynchronous or synchronous labs. At our own institution, each of these practices have been explored. In the Spring of 2021, based on lessons learned from the previous online semester, the authors redesigned and co-taught one of our introductory physics lab courses. The adapted course was rooted in our traditional in-person lab; however, it was strongly influenced by principles from the Institute for Scientists & Engineer Educators (ISEE) Professional Development Program (PDP) (Metevier et al. 2022).

In our approach to mitigating challenges, we implemented strategies to improve student learning through various avenues, such as increasing instructor-student communication, emphasizing peer collaboration, providing video tutorials, and taking a modular approach that incorporated both simulation and hands-on experiences. We received positive feedback from students in several of our implementations, which have been observed and reported by instructors from other physics laboratories. For instance, Klieger & Goldsmith (2019) and Dark (2021) found that utilizing online communication tools (e.g., forums, WhatsApp) in addition to email made the instructors more accessible to students outside of the traditional course hours. With an on-demand communication tool, troubleshooting of experiments could happen faster, interactions could be improved between instructor-students and among students, and additional functionality could be taken advantage of, such as file sharing and internet access. Additionally, independent of the online transition, more and more physics labs have incorporated mobile sensors, and computer simulations (“Filter - PhET Interactive Simulations” n.d.; Staacks et al. 2018a; Staacks et al. 2018b; Sukariasih et al. 2019) for the benefit of combining physical and online methods to augment students’ learning.

Given the foreseen continuation with online labs, we sought to create hands-on modular lab experiments where students could work individually and in teams both synchronously and asynchronously for an optimal self-paced format. It was important to us to include synchronous and asynchronous modes as a recent study by Guo (2020) found a larger grade drop for undergraduate students who participated asynchronously in an online introductory physics lecture class compared to those who attended the live online class. Our lab incorporated both synchronous and asynchronous components; however, students were still connected during asynchronous meetings via open office hours and online communication tools. The decision to build our modules around hands-on experiments with their own hardware kits was reinforced by the findings of Klein et al. (2021), who found that students reported greater success in understanding when gathering their own data either through simulations or real experiments as opposed to receiving canned data sets.

In this paper we present our experiences adapting a traditional, in-person introductory physics laboratory course to be hands-on and inquiry-driven in an online setting. Some of the explored techniques included the incorporation of video tutorials, synchronous and asynchronous work, and several online communication tools.

2. Course/lab background and general overview

General Physics with Laboratory, course numbers PHYS41/PHYS42, is a two-semester, introductory, calculus-based physics course for non-majors with a lecture and a laboratory component. PHYS41 mostly covers Newtonian mechanics while PHYS42 spans thermodynamics, electricity and magnetism (E&M), and optics. This paper focuses on the lab component of the PHYS42 course. The PHYS41/PHYS42 sequence is primarily geared toward pre-med students but other students sometimes enroll to satisfy lab science major and graduation requirements.

As depicted in Figure 1, the class demographics for our PHYS42 lab (academic year 2021) included students from neuroscience, molecular biology, chemistry, mathematics, and other fields including

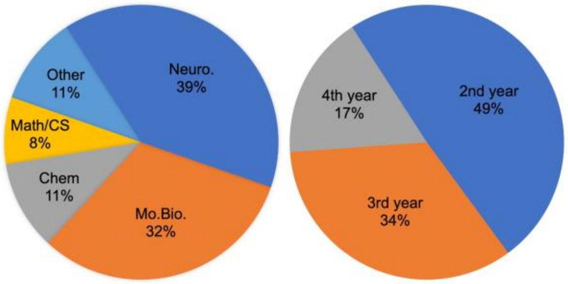

Figure 1: Student Demographics. A breakdown of declared majors (left) and class demographics (right) for students enrolled in PHYS42 (Spring 2021). The primary audience is 2nd and 3rd-year, pre-health STEM majors.

public policy analysis. Most students taking the course were in their second or third year, but a few were seniors. In addition to teaching non-major students about the application of physics to non-physics disciplines, the lab portion of the course has historically focused on teaching students physics laboratory skills. These skills include working with hardware (oscilloscopes, multimeters, lasers), basic instrumentation and experiment setup, and measuring and propagating uncertainty.

2.1 Historical lab structure

Prior to 2020 (pre-COVID), the PHYS41/42 laboratories were held in person, once a week in a 3-hour block. Throughout the semester, 10-12 standalone labs would be performed with new topics introduced weekly. In a typical week, students would be introduced to new material, complete a lab exercise in groups, perform a group check-out "interview", and then submit an informal written report each week. Following an initial mid-semester move to online learning in the Fall 2020, the PHYS41 lab was taught fully remotely. Though it kept some traditional aspects of in-person instruction, such as self-contained labs and submission of written lab reports, a few adjustments were made in response to being online, such as increasing software-based lab exercises and limiting meeting times to alternate weeks to minimize Zoom fatigue. Additionally, while the exercises were carried out in a group setting, the weekly reports were submitted in rotation by a single student in the group. The modified format worked well for some students. However, over the course of the online semester, the pedagogical impact of second-order challenges such as variable time zones, technological and software troubleshooting, and limited community building (instructor-student and student-student interactions) emerged.

2.1.1 Pre-COVID course surveys

In designing this lab course, a primary goal was to improve the online experience; however, we also wanted to use the opportunity to take a fresh look at the course as a whole. To do that we reviewed course feedback from previous years, prior to shutdown. Specifically, we tried to gauge which labs students found most useful from previous surveys and weighed these against which labs we (as instructors) thought were necessary for the course learning outcomes. We then assessed which labs could be modified to work in an online setting and which would require in-person labs. As an example, in pre-COVID surveys an E&M LED blinker circuit lab was consistently rated highly by students. Part of the reason for its popularity was that it included hands-on components in which students learned soldering skills. Though we couldn't offer that lab in its original form, we sought ways to maintain the do-it-yourself aspect of the lab that students found empowering. Some of these modifications that allowed for online adoption will be described in future sections.

2.1.2 Post-COVID, pre-course survey

Prior to the semester, students completed a survey about their experiences with remote-learning labs, highlights from which are summarized in Figure 2. Some overarching challenges that the students faced included Zoom fatigue, remote troubleshooting, and working across time zones. The most frequent adversities mentioned were laborious labs, inefficient communication with the instructor, and lack of community building with classmates. Recognizing that there is no single solution to resolve all of the raised concerns, we implemented a shotgun approach and attempted to mitigate challenges with a host of small changes. In the next section we describe our approach in further detail, but some examples include limiting the synchronous lab component to a maximum 2-hour window and incorporating various online tools for troubleshooting (Miro), communicating (Sakai and Slack), and software training via video tutorials (Vidgrid).

3. Revamped lab design

Informed by a combination of pedagogical principles, pre-class feedback (described in Section 2), and various logistical constraints, we aimed to create an effective online inquiry-based lab experience that aligned to class content and emphasized collaborative learning. In terms of logistical challenges, we had to design around the reality that: resources normally exchanged in lab, such as handouts (outgoing) and reports (incoming) would need to be moved online; lab hardware would need to be put online or individualized and mailed to students ahead of time; and additional flexibility would be needed to accommodate scheduling challenges and technical limitations.

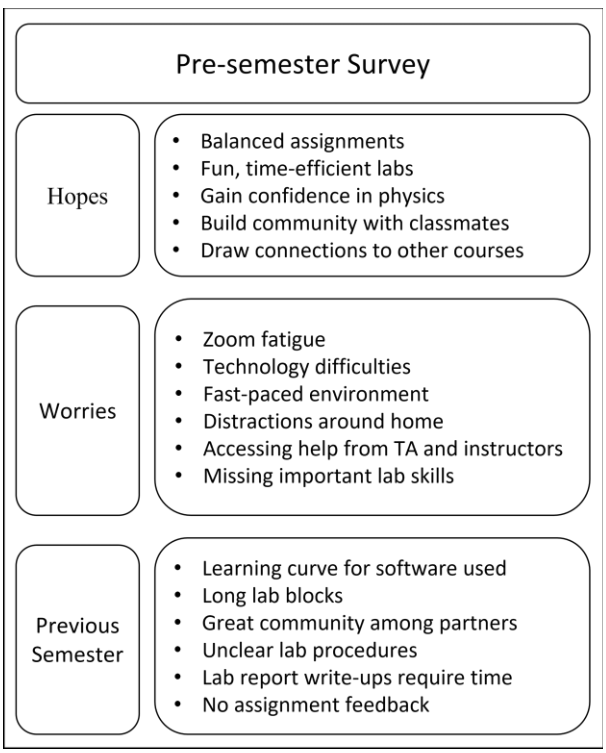

Figure 2: Pre-semester Survey Highlights. A summary of the pre-course student survey administered three weeks prior to the start of the semester. The survey followed students' first fully-remote semester, so much of the feedback related to online learning concerns; however, much of it applies more generally.

3.1 Semester module structure

The decision to abandon weekly, self-contained labs in favor of a modular lab structure allowed us to divide the semester into five multi-week modules, spanning the topics of thermodynamics, electricity and magnetism (E&M), and optics (Fig. 3). The primary benefit of the modular structure was that it allowed us to unpack the schedule and revisit material over multiple weeks. The extra time was utilized to emphasize student inquiry and reflection and encourage students to both self-pace and engage collaboratively with their labmates.

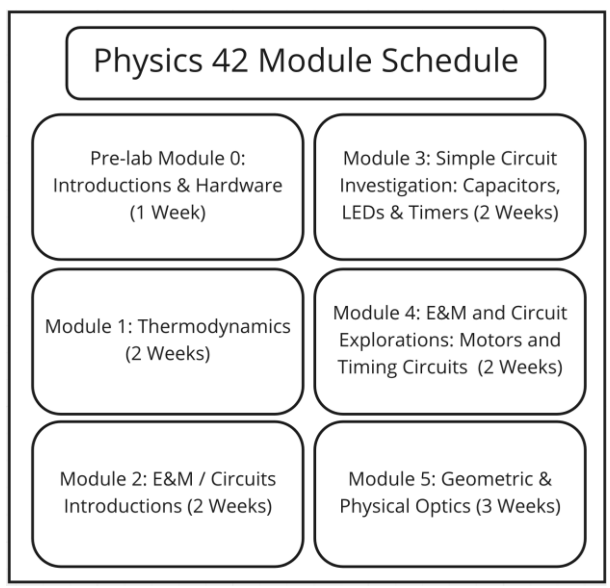

Figure 3: Lab schedule overview. A module-by-module breakdown for our 5-module, 12-week lab course. After the initial introduction week, all content modules were 2-3 weeks in duration.

The transition from historically self-contained, focused weekly labs to a more self-guided modular structure represented a significant culture change that required a ramp-up. Week one of the lab course was focused on introductions (ourselves to students and students to each other) and logistics (presenting the lab structure and expectations). Hardware kits were sent out after the first meeting and, to allow time for transit, the first module on thermodynamics (weeks 2+3) was designed around pre-prepared online resources. By the start of module two (week 4), all students had received their kits, so the remaining labs allowed for individual hands-on hardware exploration. An unexpected outcome of this design choice that will be discussed in Section 5 is that students developed strong opinions on the pros and cons of the labs designed around the online materials (module 1) in comparison to the hardware kits (modules 2-5).

One major concern we had with remote labs was that students would have a hard time connecting with each other and as a result, struggle to collaborate effectively as lab partners. The issue was compounded by the fact that students would tend to work more independently and potentially self-isolate when having individual hardware setups. Two pre-semester design choices were made specifically to address this concern. The first was a pre-lab assignment before our first meeting in which students submitted short 30-second "unfun fact" video introductions of themselves that were posted online and then viewed and commented on by their classmates. The goal was to start forging connections even before our first meeting. The second design choice made to encourage collaboration was the replacement of individual written lab reports with weekly 5-10 minute group checkout videos. Though many of our students were initially reticent about recording themselves, by the end of the semester, it turned out to be one of the defining positive aspects of the lab.

3.2 Lab module structure

3.2.1 Lab component overview

Individual weekly lab sessions were generally broken up into three components as outlined in Figure 4. There were pre-lab/background components that students were expected to complete prior to lab; there were model/investigation components in which students utilized their hardware kits and online resources such as simulators; and finally, there was a synthesis/reflection component in which students "closed the loop" on their investigation and reported their findings. These components were designed to be progressively more collaborative, with the first being mostly independent and

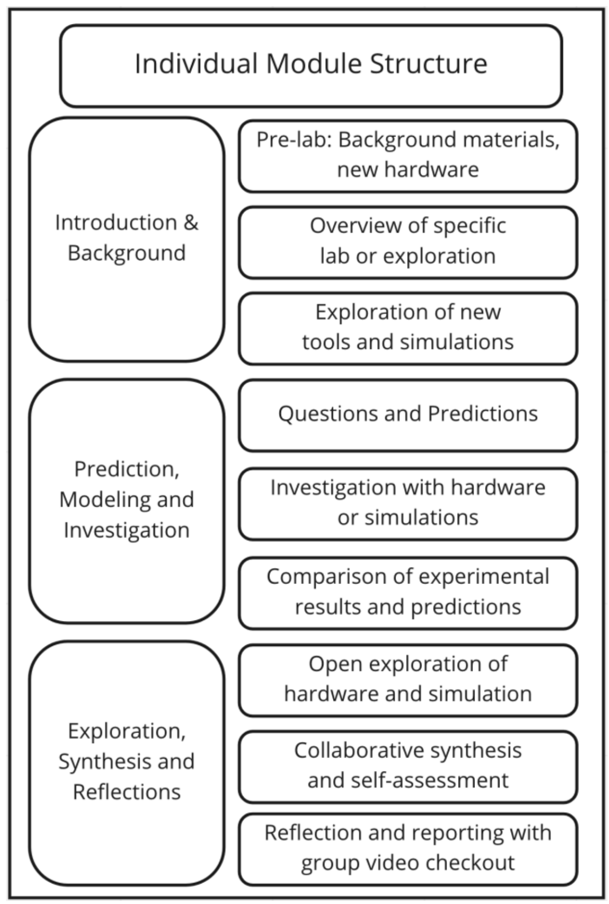

Figure 4: **General format of an individual module.** A typical multi-week module is broken into multiple small components that broadly fall into the categories on the left. Examples of representative lab exercises are shown to the right. Not all of exercises are associated with each module.

asynchronous, the second being synchronous with a mix of individual and collaborative effort, and the last being synchronous and entirely collaborative in nature.

3.2.1 Pre-lab introduction & background

Lab materials and pre-lab tasks were posted online 2-4 days prior to lab on Sakai, an open-source learning management system. Since the labs were designed to be aligned with course material, the pre-lab tasks had an emphasis on tools and techniques over topics. They typically included a mix of short, practical background videos introducing hardware (e.g., breadboards or diode lasers) and tools (e.g., digital multimeters or error analysis techniques). In addition to priming the students in general, the pre-labs were designed to offer resources that students could engage with at their own pace. Particularly for students with limited prior hardware experience, having to learn new tools on the fly can be intimidating and distracting, so resource-rich pre-lab exercises were meant to level the playing field between students with varying degrees of lab experience. As an example, a digital multimeter (DMM) tutorial that could be worked through with their own device prior to lab was more accessible than the historical approach of new (typically shared) hardware being introduced in a group setting during lab. The fact that all students had their own hardware kits and therefore the opportunity for independent exploration turned out to be one of the key benefits of the online lab experience.

3.2.2 Prediction, modeling, & investigation

The inclusion of all introductory content into the pre-lab effectively eliminated the need for drawn-out lab lectures. Consequently, the synchronous part of each weekly lab started with a lab-wide Zoom check-in that allowed students to reconnect through short weekly icebreakers, engage in Q&A, and troubleshoot any pre-lab issues.

After our check-ins, students were allowed to move directly into their breakout group of typically three students each and start working through the interactive portion of the lab, which had been posted with the pre-lab a few days earlier. Lab work varied from module to module; however, it generally included a mix of predicting experimental outcomes with theory and online software simulations, hardware assembly and troubleshooting, data collection and analysis, and comparison to predictions and simulations. Throughout this section of the lab, a teaching assistant and the instructor would continuously cycle through the breakout rooms.

With each student having their own hardware kit and independent access to software simulations, parts of the lab amounted to parallel play in which students would assemble their hardware and run software simulations alongside one another. One major benefit of this approach was that, in contrast to our in-person labs where groups typically work with a single hardware setup and students sometimes either default to an observer status or settle into specialist roles (e.g., hardware assembly, data-taking, data analysis), all students wound up taking ownership of multiple aspects of the lab. Another unexpected (but important) benefit of working on independent setups is that students became skilled at troubleshooting not only their own hardware, but also those of their group mates.

All students were responsible for their own hardware, but there remained opportunities for students to divide and conquer. For instance, students within a group might take advantage of having multiple setups by exploring different predictions and then comparing findings within their breakout group.

Throughout the lab sessions, groups could communicate with other groups via one of two collaborative tools: Slack, for quick communication, and Miro, a collaborative online whiteboard for sharing designs and outcomes. Though most of the lab was spent working in group breakout rooms, the entire lab would gather for mid-lab share-outs and planned breaks while transitioning from one phase of the lab to another.

3.2.3 Exploration, synthesis, & reflection

The final, open exploration and reflection phase of a given lab is meant to ensure that students don't get stuck in a purely "build and measure" mentality. It is designed to ensure that students make time to reflect on the lab process and synthesize their discoveries beyond the prediction and testing phase. In this final phase, students are encouraged to pursue more open explorations either individually or as a group. These explorations are the types of things that often get swept into the "future exploration" section of a report; however, we leveraged the independent hardware setups by consciously carving out time for explorations and then further incentivizing it with the structure of the video check-outs. Rather than simply recreating a video version of a classical lab report, students were encouraged to report on inquiries and discoveries that went beyond the prescriptive aspects of the lab. We found that directing students to prioritize discussion of their process promoted exploration throughout the lab.

Finally, it is worth noting that although the bulk of the lab work was performed synchronously during our weekly group meeting time, once the module structure was well established, we gave students more leeway to work asynchronously. Some students opted for this path, but most still took advantage of our weekly meeting time to work as a group.

3.3 Online and hardware resources

Our implementation of an interactive, remote lab experience was enabled by a suite of online collaborative tools, software simulators, and relatively low-cost, off-the-shelf hardware. This lab would not have been possible even a few years ago in its current incarnation, so it is worth highlighting some of the tools and their applications.

We used Sakai, the open-source learning management system, as our central organizational hub. All lab and pre-lab materials, including videos, tutorials, assembly guides, and links to external software tools were posted on the lab Sakai site. Zoom was our primary meeting venue; however, as mentioned above, collaborative tools used in parallel included Slack and Miro for inter-group communication and exchange. Finally, Vidgrid, was used for student-created self-introduction videos, instructor-created hardware assembly tutorials, and collaboratively-created group check-out videos.

The primary simulation tools used throughout the class included Falstad for electronics and Wolfram demonstrations for optics. Additionally, students installed Fiji for thermodynamics video analysis, Logger Pro for general data analysis, and PhyPhox (on their smartphones) for parts of the electronics modules.

Hardware kits (see Appendix) included low-cost diode lasers, digital multimeters, and simple electronics breadboards and components. Combined with the online and downloaded software tools, we were effectively able to fill-in for much of the expensive lab equipment typically used in our labs, such as oscilloscopes, microscopes, lasers, optics, and high-speed sensors and cameras.

4. Example lab modules

In this section we walk through some example lab modules with a focus on E&M and electronics, which includes modules 2, 3, and 4. The material, structure, and flow of the modules along with details and images of online resources will be highlighted. Connections will be made to the description of the lab structure in Section 3.

4.1 Pre-lab components

Rather than traditional pre-labs in which students work through a physics exercise they will investigate in lab, the pre-labs used throughout this course were generally geared toward introducing students to their hardware via photo guides and video tutorials. The first few pre-labs for the electronics module include a hardware list to take inventory of their lab kits and video tutorials on digital multimeters (DMMs) and electrical prototyping breadboards.

Each pre-lab was meant to be completed asynchronously to ensure that students had sufficient opportunity to familiarize themselves with the hardware they would be using during the lab. As another example, during an early E&M pre-lab, students were given a video tutorial and a short quizlet on how to connect components on a breadboard, shown in Figure 5.

4.2 Module 2: Fields, potentials, and DC circuits

The first module in the electricity and magnetism series introduced students to electric fields by having them interact with an electric field simulator. Students first plotted the voltage and electric field around a simulated charge as a function of distance and compared the two. They then used their hardware kits, conductive paper and DMMs to sample real potential fields.

As a circuit introduction, students were first given an exercise to organize their resistors to learn how to decipher color code values. They then used Falstad, an online circuit simulator in conjunction with their hardware kits to create simple series and parallel circuits, predicting and testing voltage drops across resistors in various configurations. Building on their investigation, students would later be asked to determine the resistor combination that would output a specific voltage of 0.5V from a 3.1V battery.

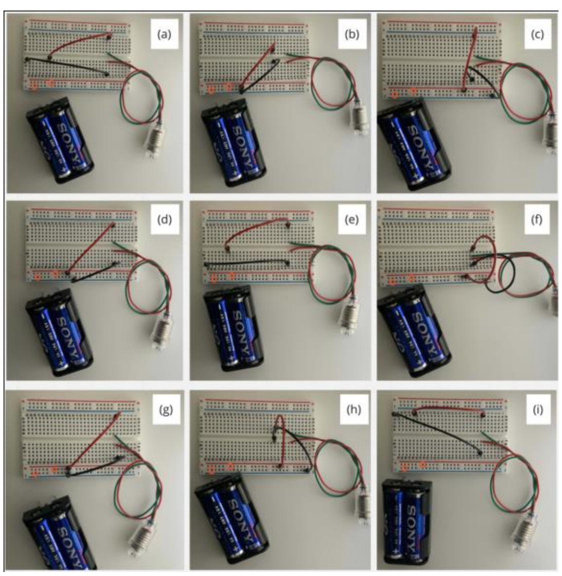

Figure 5: **An example pre-lab, visual quizlet exercise.** As part of an electronics pre-lab exercise, students self-assess their understanding of breadboards with an image quizlet in which they are tasked with identifying functional vs. mis-wired circuits.

Another task in this first module had students investigate Ohm's Law. Students made predictive plots of current vs. voltage for each of their resistors and then verified their prediction with the simulation tool and hardware. For all of these exercises, in which simulations and hardware were coupled, students were encouraged to work collaboratively by dividing software and hardware tasks and comparing their findings. To mitigate hardware challenges, photo-guides were provided to students showing them concepts such as connecting a resistor to a battery and measuring current with a DMM in the ammeter setting. One set of example photos describing breadboard connections is shown in Figure 6.

For their video submissions, students were prompted to explain the following:

- The relationship between electric field and electric potential.
- The student's developing understanding about energy, current, voltage, etc.
- Any new insights about electricity or electronics.

Group submissions included students having round table discussions on the material with a few students submitting individual videos stepping through the prompt.

4.3 Module 3: Capacitors, LEDs, and the 555 blinker circuit

After familiarizing themselves with resistors and DC circuits, students were exposed to more complicated circuit elements like capacitors and LEDs. At the beginning of the second E&M module students were shown the full blinker circuit they would

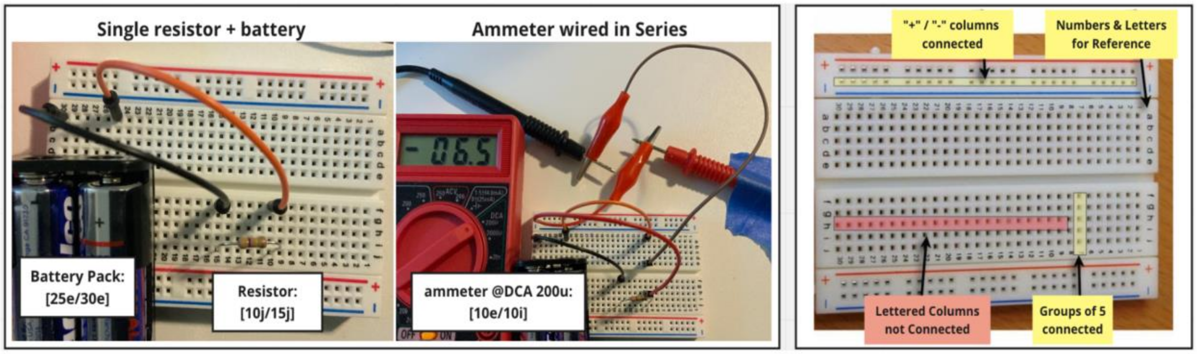

Figure 6: An example hardware photoguide. A sample image from the course website illustrating breadboard functionality. Detailed hardware photoguides were used throughout the course to mitigate some of the troubleshooting challenges associated with remote labs.

eventually build. After seeing this complicated circuit, the task was broken down into bite-sized tasks using sub-circuits (Fig. 7).

The first part of the circuit that students looked at was the capacitive input stage, which used an RC circuit to control the rate of blinking at the output of the 555 chip. Students studied RC time constants using the scope functionality in Falstad to measure time-dependent signals on their simulated circuits. In addition to serving as a stand-in for a traditional oscilloscope, Falstad's ability to visualize current flow played a central role in solidifying students' understanding of RC circuits.

In the exploratory phase of the lab, students were asked to make predictions on the current flow for an RC circuit connected to a switch. Afterwards, students were given a guided exercise to vary the resistance connected to their capacitor and measure the time constant.

The second part of the blinker circuit that students explored was the LED output stage. They first explored this sub-circuit using the simulation tool. The class was asked general questions to guide their exploration (e.g., What happens when two LEDs are connected facing each other? What happens when you switch the polarity of an LED? How does resistance affect the brightness?). After exploring LEDs in simulation, students again moved to their hardware to look at the properties of their LEDs.

Studying the circuit components individually led up to the construction of the final 555 blinker circuit. The approach of building the circuit up from its various components is a significant departure from previous implementations in which students were given the circuit as a soldering exercise and told precisely where to place components without explanation. In this self-guided version, students built up an understand of why and how they were connecting certain components together.

The final circuit construction was completed asynchronously to reduce the stress of having to finish their circuit in a fixed amount of time. Photos and a video guide on how to assemble the blinker circuit were provided as a resource.

After construction, students were prompted to explore their circuit and human biology with some guiding questions, such as:

- Experimentally determine your eyeball's flicker fusion threshold by designing circuits just above and just below the frequency where you notice blinking.
- Use your phone camera to record the LED blinking. Typical cell phone cameras can record at frame rates that are 2-5x higher than your eye.

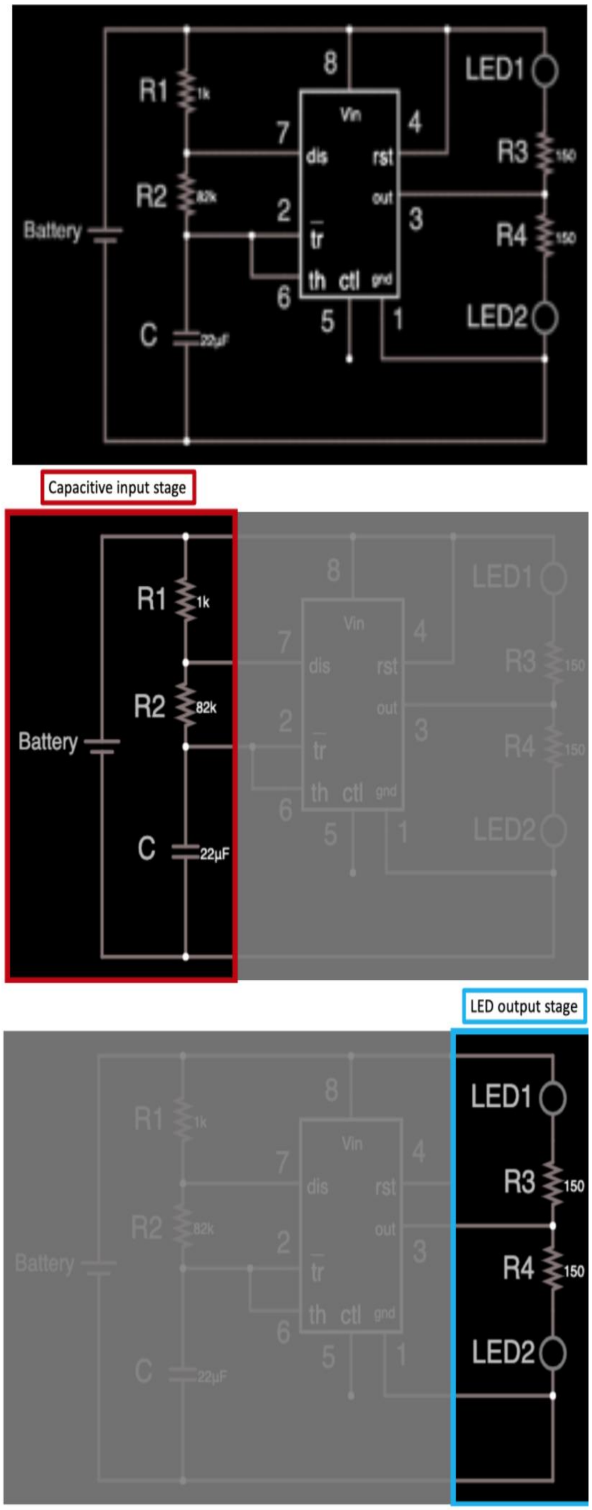

Figure 7: Photoguide for Falstad 555-timer simulator: The schematic of the 555-timer blinker circuit (top) and the images used to highlight each of the individual sub-circuits (capacitive input stage, middle and LED output stage, bottom).

- Swap R1 & R2 and discuss what happens based on what you previously learned about the RC time constant.

The final video submission for this module was a video that asked students to find a creative application for their circuits, noting that any interesting videos would be shared with the rest of the class. Video submissions included everything from basic blinker circuit walkthroughs to exploration responses to creative implementations of a 555-timer circuit.

4.4 Module 4: Electromagnetic motor and blinker circuit exploration

In the first week of the final E&M module, students were first instructed in how to construct an electromagnetic motor from their hardware kit components. Students were then asked to use a mobile phone applet, PhyPhox to measure the frequency of their motor using the generated magnetic field.

The final week of the electronics module culminated in an exploration of the motor and the blinker circuit. Students were asked guiding questions for each device and given free time to explore their ideas. The final product was a video that offered students a chance to creatively explain the concepts they learned. Collaborative submissions included short tutorials, motor performance clips and documentary-style shorts.

5. Outcomes

In this section we share some take-aways based on surveys given to the students, as well as anecdotal feedback gathered by instructors and mentors. We hope that these results will inform future iterations of this and other related introductory labs.

It is worth noting some of the limitations of our self-assessment. First, we do not have survey data from previous semesters, so we are not able to directly compare historical outcomes. We also do not have a control sample of lab sections taught with a more traditional method during the same semester.

On the other hand, informal anecdotal feedback throughout the semester and a comparison of our early vs. end-of-semester surveys gave an indication for which of our broad pedagogical goals were achieved and which went unmet. More quantitatively, we also saw strong trends in the survey data between modules that offered insight into which techniques were well received and merit further exploration. Finally, the survey data also reveals an overall positive sentiment toward the lab experience in general.

5.1 Pre-semester survey

Student feedback was acquired throughout the semester in the form of pre-, early- and end-of-semester surveys. The primary purpose of the surveys was to guide our choices and identify the successes and failures of our efforts.

The pre-semester survey focused on hopes and worries that students had about the upcoming semester. This guided us in planning the course to mitigate the worries that students had. This strategy was highlighted in section 2.1.2.

In response to our students' hopes, we focused on building confidence in physics concepts and experimental techniques by aligning lab and class content and providing a collaborative environment for engagement. We tuned the class to address some of the major remote learning challenges that our students cited, such as zoom fatigue during long online lab sessions, isolation and lack of community with peers, and inefficient communication with instructors.

5.2 Early-semester survey

We gave the early-semester survey approximately four weeks into the semester. At this point, students had completed the first module and were in the middle of the second. Results from this early survey were evenly split (roughly 50/50) between students who had positive sentiments toward the course and students who had some reservations based on the first few modules. Positive students showed appreciation and optimism for the structural changes (such as the video check outs), the upcoming hands-on labs, and the collaborative environment we had been fostering. Students who had reservations showed concerns about the duration of the lab in general. To the latter point, almost half of all respondents mentioned Zoom fatigue as a limiting factor. The range of sentiment was not inconsistent with the hopes and apprehensions that students voiced in the pre-lab survey.

Two major shifts came after that first survey. The first was already planned into the course and the second was a response to the survey. The planned shift was the move to hands-on labs in which students each worked with their own hardware kits. It was simply delayed until module 2 due to shipping constraints. The latter was an intentional change to creating more asynchronous work that students could engage with outside of formal lab hours with or without their groups.

5.3 End-of-semester survey

After week 4 and the adjustments described above, we committed to the modules and methods described in Section 4 and then surveyed the students again at the end of semester. In contrast to the mixed sentiment reflected in the early-semester survey, the end-of-semester survey was strongly positive with roughly 90% of all free response comments providing strongly positive feedback on various aspects of the class. The positive comments from the earlier survey relating to the structure and organization that allowed for collaboration and exploration were reinforced. Concerns related to the initial remote lab were completely replaced with an appreciation of the hands-on electronics and optics labs that soon followed. Most significantly the initial concerns related to Zoom fatigue were almost entirely mitigated and replaced with glowing comments about our implementation of checkpoints, forced breaks, and asynchronous components that facilitated engagement, even online. A sampling of

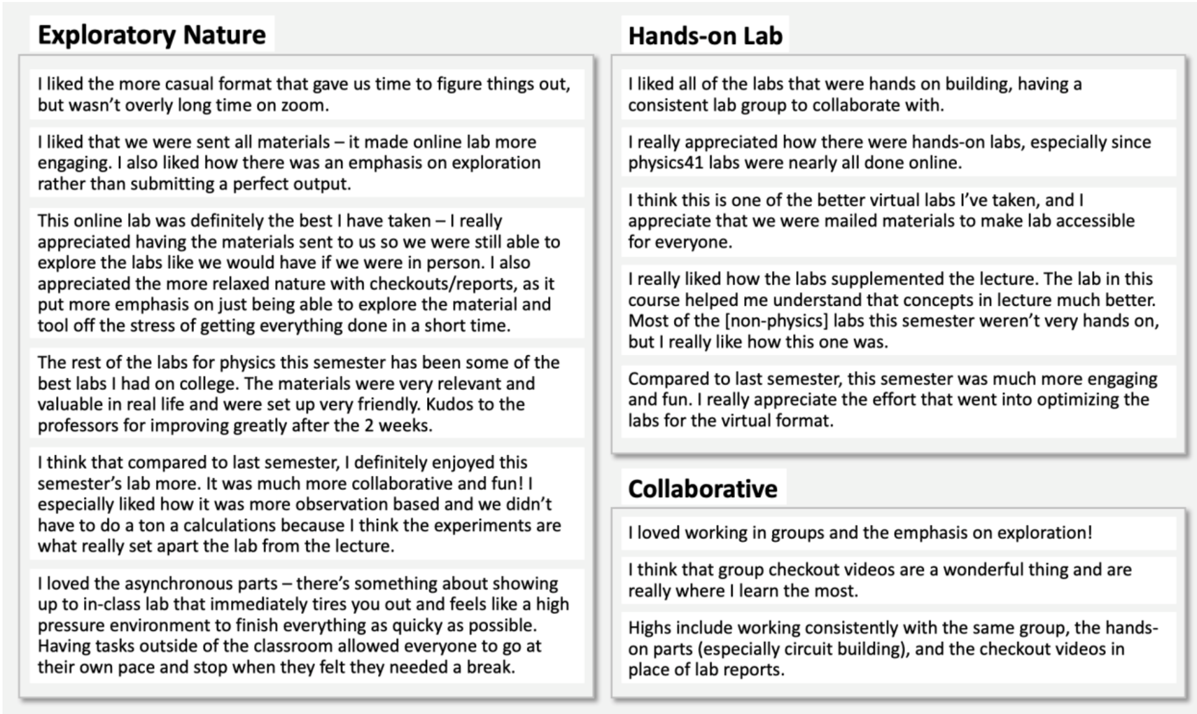

Figure 8: End-of-semester survey highlights. A summary of the end-of-semester student survey. Feedback spanning a broad range of topics was overwhelmingly positive. Students particularly expressed appreciation for the self-directed, hands-on nature of the course, as well as its emphasis on collaborative learning.

the end-of-semester comments are provided in Figure 8.

In addition to the qualitative feedback, we also solicited some quantitative assessments related to each of the individual modules. Though we don't have comparable data from other semesters, we found there was significant variance between the purely online module that we started the semester with and the following labs that utilized the lab kits that were mailed out to students. Histograms in Figure 9 show end-of-semester ratings of different aspects of each module. For brevity, only responses for Modules 1, 3, and 5 are shown, but Modules 2 and 4 look almost exactly like those of 3 and 5. The takeaway is that students strongly preferred modules 2-5 which all had significant hands-on hardware components compared to Module 1 which was carefully curated but used canned data that we took and supplied to the students.

6. Conclusion

We reconfigured the introductory physics lab to directly address learning challenges that were introduced during unprecedented online teaching. We focused on incorporating both hands-on experimentation and simulation tools while also adopting techniques to mitigate the wide range of challenges students faced in previous online lab classes.

There were many lessons to be learned from this experience about how to successfully design and implement self-guided, hands-on labs online. Many of those lessons will inform the future design of our in-person labs. Specifically, we plan to retain lab features like pre-lab hardware tutorials and self-paced exercises that empowered students from varying backgrounds to confidently engage in lab. We will explore a move to more individual hardware setups even for in-person labs, even if it comes at the expense of sacrificing some high-end hardware.

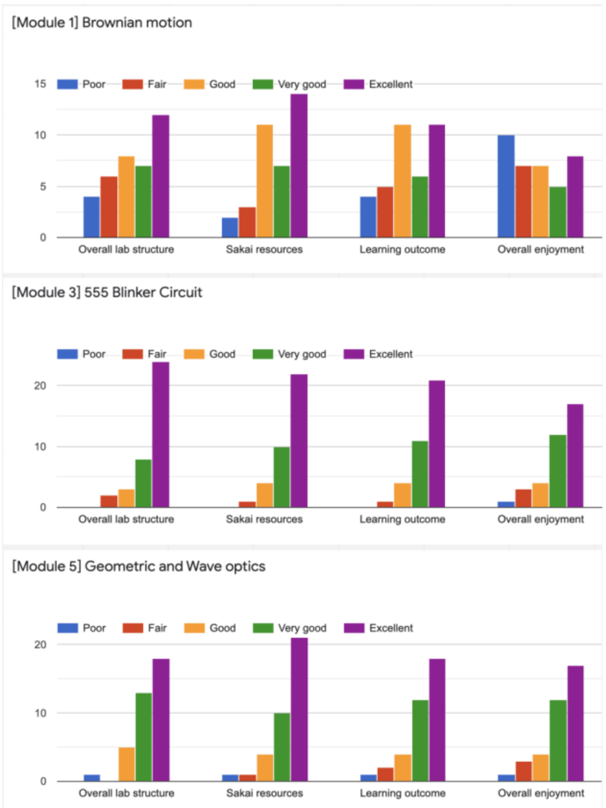

Figure 9: Quantitative end-of-semester survey results. Ratings for representative modules spanning thermodynamics, E&M and optics reveals a strong preference for the hands-on modules designed around individualized hardware kits. Results from modules 2 & 4 (not shown) align strongly with mod-

Finally, in terms of assessment, we will retain the collaborative exploration and reporting practices such as group reflections and submissions.

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Appendix A

The following hardware kits, which were used for modules 2-5, were assembled and sent to each student prior to the semester. Figure A1 lists the contents and approximate per student cost of all items in the optics and E&M lab module kits (Fig. A2). The cost estimate of ~$25/student is based on the bulk purchase of typically 80-100 units. By implementing simple components, we were able to keep the total per student cost well below the cost of a typical textbook despite the inclusion of multiple laser diodes, optics, a digital multimeter and electronics hardware suggests. Hardware kits were packaged in USPS priority flat rate small boxes which added roughly $9 per unit in shipping costs.

Module	Item	N	Cost per Student
Optics	Laser (readboard diode)	2	$1.30
Optics	Laser Holder	2	$0.08
Optics	Putty for Laser mount	2	$0.04
Optics	Convex Lens (+68mm)	1	$0.65
Optics	Concave Lens (diopter=5)	1	$2.00
Optics	Optic Holder (Binder Clip)	2	$0.12
Optics	CD grating fragment	1	$0.20
Optics	DVD grating fragment	1	$0.20
Optics	Single Slit (pencils+rubber bands)	2	$0.13
Optics	Grating Holder/Clips (Medium)	2	$0.12
Optics	Index cards (3"x5")	10	$0.15
Optics	Whiteboard marker	1	$0.28
Optics	Sheet protector+Card stock	1	$0.35
Optics	Tape Measure	1	$0.19
Optics	Painter Tape	4	$0.15
Optics	Film Canister	1	$0.20
Optics	Match Stick	1	$0.01
Optics	Alligator Clip to Wire	2	$0.60
Optics	Magnetic balls 5mm	5	$0.40
E&M	Homopolar magnets (15mm)	3	$0.72
E&M	Digital multimeter	1	$6.79
E&M	Batteries (AA) (2 per student)	2	$1.20
E&M	Battery holder	1	$0.65
E&M	Light bulbs	4	$0.96
E&M	Light bulb mounts	4	$2.00
E&M	Conductive paper	1	$1.32
E&M	Breadboard	1	$1.61
E&M	Breadboard (Mini)	1	$0.67
E&M	555 Chip	2	$0.43
E&M	Resistors (variety 8-pack)	3	$0.36
E&M	Capacitor (2.2u)	3	$0.39
E&M	LED (Red)	2	$0.25
E&M	LED (Green)	2	$0.25
E&M	Breadboard jumpers/wires	1	$0.98
	Lab Hardware Total		**$25.75**

Figure A1: **Hardware Kit Bill of Materials.** The total lab kit cost per student was less than $35 (including shipping costs) when items were purchased

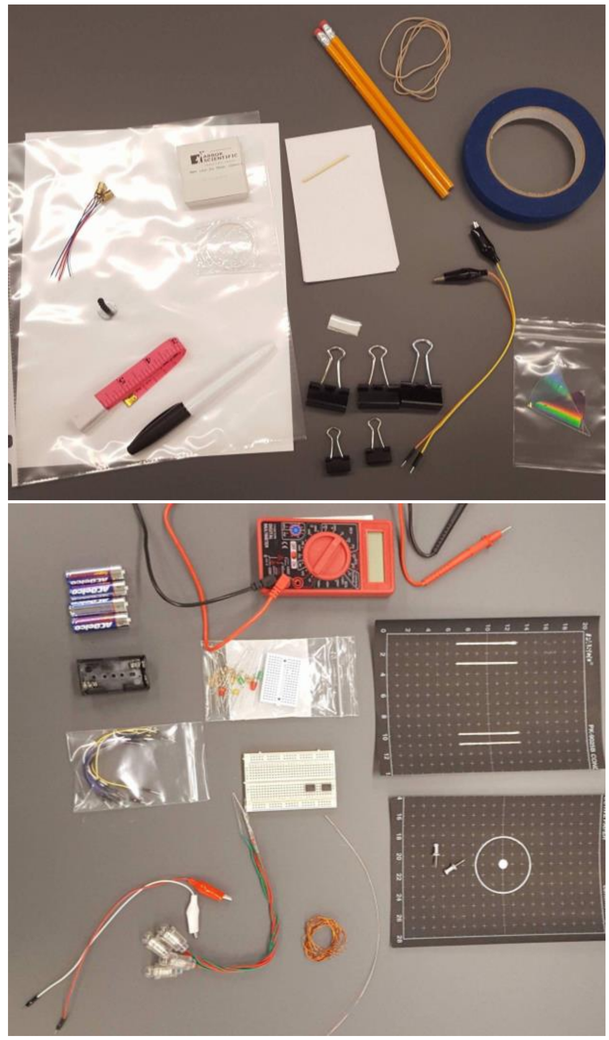

Figure A2: Hardware Kits. Materials kits shown above include most of the materials sent to students for the optics module (top) and the E&M modules (bottom). A few items missing from the photo include the film cannister, match sticks and magnetic balls.