Introductory Physics Labs: A Tale of Two Transformations

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A significant challenge physics faculty face teaching introductory labs is engaging students in authentic science practices.[1–3] Another has been highlighted given the current global pandemic—how to engage students in our laboratory courses while maintaining appropriate social distancing and hygiene standards. We have chosen to answer these challenges by transforming our labs…twice. We discuss the rationale behind the first transformation to a practice-focused curriculum. In March 2020 we needed to transform our labs again, this time to accommodate online learning. This paper discusses two chief questions: "What are we doing to engage students in science practices?" and "How did we make all of this work online?"

Introduction

The physics labs at our institution in fall 2016 very much mirrored the national narrative. The lab curriculum had been largely unchanged for about 20 years. Moreover, the equipment and techniques used by students was outdated—triple beam balances and hand-drawn graphs were standard. That same year, as part of an interdisciplinary team interested in engaging students in and assessing scientific practices, we secured funding, both internally and from the NSF, to change this status quo in physics, biology, and chemistry. All three departments transformed their labs using the Argument-Driven Inquiry (ADI)[4–6] pedagogical framework, which has been specifically designed to engage students in authentic science practices. The ADI methodis very much in the spirit of transformations such as Modeling Physics[7] and the Investigative Science Learning Environment (ISLE).[8] Oftentimes, both Modeling Physics and ISLE are implemented in studio-style or other active/interactive lecture classrooms, whereas ADI is lab focused. The common use of hybrid courses for Modeling and ISLE implies a shorter time scale for their learning cycles, for example, an ISLE cycle often takes place over the course of a week, whereas the cycles that we use in ADI take place over four weeks. For the institutional transformation of our physics labs with ADI, we also utilized the AAPT lab recommendations to inform our curricular choices.[3]

We were satisfied with our progress when the global COVID-19 pandemic forced a shutdown in March 2020. With students off campus, we had to abruptly shift our delivery to an online format and quickly realized that many of the face-to-face activities had to be adapted to online use. Going forward to fall 2020 (and beyond), we have further adapted what we are doing so that students can still participate in a hands-on laboratory experience in an online laboratory course.

Instructional context

Labs are supervised by the second author (MWS), but sections are run by graduate TAs (GTAs). The transformed curriculum was jointly written by both of the authors. GTA training was also greatly enhanced when the new lab curriculum was put in place. Both authors, along with colleagues in biology and chemistry, run training for all GTAs in biology, chemistry, geology, and physics as these disciplines are all using the same curricular format for their labs. Author 2 runs a weekly prep meeting with the GTAs, and Author 1 (SFW) and the research team have supervised various aspects of the transformation especially important for research such as curricular implementation[9] and assessment grading practices.[10]

Transformation #1: Argument-Driven Inquiry

Argument-Driven Inquiry (ADI) is a pedagogical method developed to make science labs in school better match what transpires in authentic research settings.[4–6] In traditional labs, we often ask students to answer questions, or measure quantities, that are well known using procedures that have been refined over time. In ADI labs, we give students a guiding question to answer experimentally (e.g., "Does the force a fan exerts on a cart depend on the mass of the cart?"). This allows students to design a procedure for an experiment that will answer that question, collect and analyze their data, and make claims based on their data. We accomplish this by having students engage in a three-part cycle:

- Pre-Lab: Introducing the context
- Proposal Development and Data Collection
- Argumentation and Peer Review

In the sections below, we will comment on each part of the cycle, focusing on both students and GTAs. Each lab course completes at least three cycles (usually four in the fall and spring), and the semester ends with a practical exam where students engage in this process on a shortened cycle without peer feedback.[10] We have provided supplemental materials with more details about each of the labs in our curriculum.[11]

Session 1: Pre-lab

Part of the goal of any laboratory is to help students develop a familiarity with certain tools and equipment common to the lab. The purpose of the pre-lab reading and activity is to give students familiarity with the equipment they will be using. For the investigation described previously, "Does the force a fan exerts on a cart depend on the mass of the cart?" students must become familiar with a few things, such as what we mean by a cart, and also obtain some tools to be able to answer this question. As a part of the pre-lab reading, students learn about linear regression—how to run it in Excel, how to interpret the output, and how we can estimate instantaneous velocity given position vs. time data. For this experiment, we give them a cart (leaving the fan off for now) and have them measure the acceleration of that cart down a ramp using an ultrasonic motion detector to collect position vs. time data. Students work in pairs and submit a brief summary of this work on the learning management system (LMS). This in-

vestigation is the first time the students create graphs, so we set norms for graphing such as helping them decide which variable to put on the *x*-axis and the *y*-axis as well as including units. Pre-lab assignments are designed to be graded in less than one minute/submission based on a rubric we provide to both students and GTAs.

Session 2: Proposal development and data collection

During this session, students work in groups of three to four on the guiding question. They develop a proposal, get it approved by a GTA, and then collect and analyze data. Our proposal development format asks students to link the scientific concept being studied—in this example case, Newton's second law—to the data that they will collect. Students also must propose a plan for analyzing their data and minimizing potential sources of error (such as friction). Once students have an approved proposal, they begin collecting and analyzing their data. This may lead them to refine or revise their method (which is encouraged). Grading for the GTAs this week is minimal (students get full credit for getting their proposal approved). However, this is the most critical week for GTA training. GTAs have to be clear that the goal is to allow a diverse number of ways of collecting/analyzing this data. This can be uncomfortable for the GTAs and students alike. Students want "the answer," and GTAs want to provide one for them. However, experimental methods certainly have an impact on experimental results. One of the goals of this curriculum is to get students to understand this and apply it as they develop their experimental procedures and evaluate their results.

Session 3: Argumentation and peer review

During this session, the students share their results in a poster session. Students finish analyzing their data during the prior week and prepare a "poster" on a whiteboard. One person from the group stays at the whiteboard while the other group members (travelers) go to other groups. The travelers learn what other groups did and compare to their results in a structured argumentation setting. Groups spend about three to five minutes at a poster and rotate so that they see at least three other posters. After the travelers return, critically, the groups spend time discussing what they saw and reflecting on their own results. What is exciting is that sometimes, these interactions actually drive groups to change their claims.[12]

After the session, each student submits a draft report consisting of three sections: an introduction to the scientific concept, a description of the experimental method or procedure, and a discussion section laying out their results and the evidence and justification supporting their results by the end of the next day. The authors have created different peer review calibration videos for the students to watch so they can look for the same things that we will grade when we get their final reports. After watching the video, students take part in online, double-confidential peer reviews of two different lab reports using a simplified rubric based on the grading rubric for final drafts. Finally, students use their feedback to revise their own lab reports. At the end of this week, students turn in their revised, peer-reviewed final lab report. This is the heaviest week of GTA grading, as each lab report generally takes about three to five minutes to grade.

Transformation #2: Online Adaptation
Sudden transition to online instruction–Spring 2020

In March 2020 the COVID-19 pandemic forced most universities, including ours, to move all classes online. Our Physics 1 and 2 laboratories had completed two out of four full investigations and the pre-lab for the third investigation face to face. We were forced to find a way to engage students in an online format while preserving the nature of the ADI laboratory experience. In addition, we gave the laboratory practical exam online. We required student investigation groups to find a method for online collaboration in which everyone in the group could participate. Tools students used were the LMS (Canvas) communication tools, WebEx (video interaction platform licensed by our university), and other online communication applications not managed by the university (e.g., group chats). We have detailed the adaptations we made to the curriculum in the supplementary materials.[11] One of the principles that we used while making these adaptations is that students should exclusively use university-supported (Microsoft Office) or open-source resources.

The pre-lab phase was managed one of two ways. As this is the most prescriptive part of the lab, intended to introduce students to data collection and analysis techniques, in-person activities were modified for online use by creating (or using) videos or simulated using Glowscript.[13] Students could collaborate with a partner asynchronously for this part of the project.

Proposal development also occurred online asynchronously. Each group produced their proposal and posted a proposal form on a discussion board for approval. The GTA reviewed proposals and provided feedback or approval. Groups used the GTA feedback to revise their proposals until they were approved. As with the prior face-to-face labs, the GTAs were looking for specific items in the proposals such as what data the students planned to collect, how they would use the data to answer the guiding question, what steps they would take to minimize errors, and how the students would quantify their uncertainty. Most proposals obtained approval after two or three revisions, but some required as many as seven revisions to obtain approval. When the GTA approved a group's proposal, they assigned the group a data set for the investigation, and the group began measurements and analysis. Groups were encouraged to revise their methods during the measurement/analysis phase if they discovered a flaw or a better way to answer the guiding question. Based on our prior experience running the class, we prepared some data sets appropriate to the different proposals that previous students had produced and provided measurements to the current students in the most raw form possible to require them to make decisions about data collection and analysis. We provided six data sets for the third investigation and 13 data sets for the fourth investigation for the Physics 1 laboratory. We provided seven data sets

for the third investigation (each group was assigned two data sets at random to compare) and 14 data sets for the fourth investigation for the Physics 2 laboratory.

The argumentation session was held in a scheduled WebEx session the week after the proposal session. Before this session, each group was required to complete its analysis and create a three-slide presentation for the argumentation session: (1) a description of their measurements, (2) a presentation of the results, including a graph or table, and (3) their argument based on their results. One member of each group gave the presentation, which was followed by questions. Students received credit for giving presentations, asking meaningful questions, and responding to questions. Following the argumentation session, students submitted individual draft reports, peer-reviewed each other's drafts, and submitted final reports in the same manner used for the face-to-face investigations.

We administered the lab practical exams for both courses in the LMS using Glowscript simulations embedded in LMS assignments. Students made measurements on the simulation and used their results to make an argument answering a guiding question.

Fully online laboratories – Fall 2020

Early on, we decided to hold our introductory physics laboratory courses online in the fall 2020 semester to preserve the group class interaction aspects of ADI, which would be difficult under social distancing requirements in place due to the pandemic.[14] Learning from some of the challenges we faced in the spring, we informed the students before the course began that internet connectivity was required and that they must have access to a computer capable of running Tracker[15] and ImageJ[16] (used in the course). We also included these statements in the course syllabus. Although we began the semester with the university open for socially distant face-to-face learning, that has since ended, and we have pivoted to online instruction only for our undergraduate students.

We developed lab kits with supplies that allowed students to perform the investigations outside the teaching laboratory so we could provide students with a hands-on experience. We purchased the lab kit items in collaboration with our campus bookstore, and the students purchased the lab kits from the bookstore. We ordered lab kit items in bulk and, where possible, directly from manufacturers to reduce the costs of the items. Each Physics 1 kit cost $20.60, and each Physics 2 kit cost $39.00. Students paid for these kits in place of a lab manual, which we provided online for this course. Lab kit materials were used for each investigation. The two video analysis investigations in the Physics 1 laboratory (one comparing the accelerations of a marble rolling up and down an incline and the other analyzing a marble collision in two dimensions) required the students to record their own videos of marbles from their lab kits using their smartphone cameras. The image analysis investigation in the Physics 2 laboratory required students to cut their own slits in aluminum foil and also create mounts for hairs to produce diffraction patterns with lab-kit lasers. The online adaptation of the face-to-face ADI curriculum has changed slightly. Pre-labs are done in groups asynchronously.

Proposals are developed in groups during the lab period, and scheduled argumentation sessions occur via WebEx during the lab period.

Discussion

We have observed a great number of successes for these transformations. First and foremost, we indeed have a lab curriculum that is aligned with national goals and standards. Furthermore, we have successfully deployed this online. Students are engaging with science practices as determined by our practical assessments, and our department culture around laboratory course instruction is invigorated. Psychometric assessment of our students' engagement with science practices is ongoing.

The transition to online learning has not gone without hiccups. Technology and access are two key factors for success in online learning environments, which were a barrier for many of our students. Our institution implemented a number of academic measures intended to support our students during the pandemic, including extending the withdrawal date and allowing students to be graded pass/fail after seeing their final grade during each of the spring 2020 and fall 2020 semesters. Other supports put in place at the institution included an extended laptop loan program. Also, remote proctoring was paid for by a grant through the university system. Our institution's Center for Survey Research published some findings in August 2020 that explain some of our observed issues.[17] The GTAs and students found communication about proposals much more difficult online than in face-to-face classes. About 10% to 20% of our students did not have reliable internet access after the transition to online learning in the spring.[17] Also, up to 8% of students did not have access to a computer once they left campus.[17] Additionally, we noticed that some students in the course did not have access to computers capable of running Tracker or ImageJ, both of which run on Windows, Macintosh, or Linux computers but not Chromebooks or mobile devices. We discovered jsTrack,[18] an online JavaScript web application for video analysis that runs on most computers including Chromebooks, but not mobile devices.

Many students could not or did not attend the online WebEx sessions or participate with their assigned groups. Once they left campus, many students found they had increased work or school responsibilities (42.1%) or additional family responsibilities (59.0%).[17] We removed non-participating students from groups and gave them an opportunity to make up their missed work asynchronously. Less than 50% of the students in the make-up groups completed their work.

Finally, we hope these changes will be meaningful long term as a lack of online labs is also a barrier for distance education students' completion of a degree. so online lab curricula would fill an institutional need.

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