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Asking Real-World Questions with Inquiry-Based Labs

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We have developed and employed a set of inquiry-based labs built around engaging “real-world” scenarios for our studio-style introductory Physics II course. In real-world situations, there is more than one path to success and step-by-step instructions are not provided. For this reason, the primary goal for these labs is to provide students with the freedom to develop collaborative solutions to open-ended challenges, where creativity and independent thought are encouraged. This approach is more akin to what they will encounter in the academic or industrial lab settings. The main challenges facing the students are developing the experimental plan and writing an in-depth lab report; in the end, the necessary measurements typically require only 5-10 minutes. The primary challenge to the instructor(s) is providing just enough guidance to keep students on the path to a feasible plan without giving away the solution. Student feedback has been very positive and we have made these labs freely available to our students and the larger physics community.

Introduction

The past few decades have seen a major shift in the ways we think about physics education. From the early pioneering work of Hake¹ to the recent meta-analysis of Freeman et al.,² it has become clear that teaching methods that encourage active engagement from students yield superior results compared to traditional lecture-based instruction, a result that holds for high schools, two- and four-year colleges, and universities. Implementing active learning in STEM courses can decrease failure rates by a factor of 1.5 while also improving attendance and raising performance gains on frequently used concept inventories.³⁻⁸

Incorporating hands-on laboratory experiments into a physics course is a seemingly obvious way to tap into the benefits of engaged student learning. Unfortunately, and slightly unexpectedly, studies of the learning outcomes of students in traditional lab courses find that there can be marginal conceptual gains and minimal improvement in student understanding of the scientific process.⁹⁻¹² This is partially due to a misalignment between lab activities and expected learning outcomes. For example, instructors expect labs enable a better understanding of the material and firsthand experience in how physics theories are tested. However, labs are often hyper-structured, instructing students to follow specific steps without considering why or how those steps relate to the physics at hand. When students are told precisely the measurements to make and, in some cases, the results to expect, they have little room to explore the scientific process. Ideally, introductory calculus-based physics courses help prepare students for future work in academic and industrial lab settings. In these environments, they will not be given a detailed set of

instructions like those in traditional labs. Instead, ingenuity and independent thinking will be key.

In order to overcome this mismatch in lab expectations and lab practice, at our university a set of inquiry-based physics labs were introduced to the second semester of the introductory engineering studio physics course. These inquiry-based labs have almost no instructions, thereby forcing students to grapple with the concepts covered in lecture and how best to apply those concepts to a practical challenge.

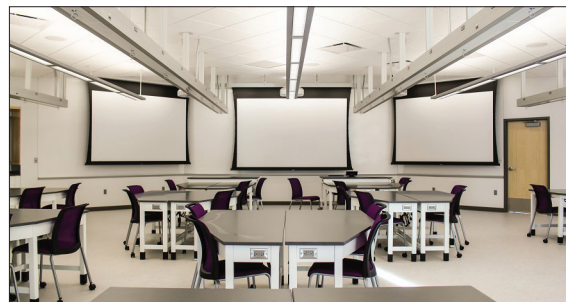


Fig. 1. The Studio Physics classroom.

The Studio Physics Classroom

Our Studio Physics courses combine the traditionally separate lecture, lab, and discussion components into a single streamlined experience offered two to three times per week (300 minutes total). During these class meetings, students naturally transition between listening to an instructor, working in groups, and participating in hands-on activities. To facilitate this type of course, students work in groups of four at tables or whiteboards (see Fig. 1). The classroom accommodates up to 56 students seated at 14 tables. The first semester of this two-semester calculus-based sequence focuses on kinematics, conservation of energy, momentum, gravity, fluids, and waves. The second semester covers introductions to circuits, electric and magnetic fields and forces, and thermodynamics. These courses are intended primarily for engineering and science majors. As the course is not split into the traditional separate components, the professor and TAs are present for the entire learning process. A wide variety of lab equipment is conveniently available in the classroom, which allows students to select their own materials for the experiments they design.

The labs

Previous to instituting the Studio Physics option for students, we offered multiple sections of lecture (typically taught by different faculty and with $N_{\text{students}} \sim 50-100$) along with several smaller lab and discussion sections (typically taught by a small army of graduate students with up to 28 students per section). The weekly lab experiences were traditional in

format, following a prescribed, step-by-step structure. There would be ~12 standalone labs per semester that may or may not be directly linked to current lecture topics. Labs were evaluated via short-answer pre- and post-lab questionnaires.

In contrast, the hands-on lab component of Studio Physics was distilled down to six inquiry-based challenges that directly flow from the “lecture” material. Each lab is structured around an engaging scenario that poses a “real-world” problem to solve, and students are provided with a list of available equipment that may be useful. Half of the inquiry-based labs developed were based on pre-existing labs and their equipment, but with the instructions dramatically stripped down. We decided to require in-depth lab reports because we removed the step-by-step instructions and pre-/post-questionnaires, and we wanted to see a full description of their experimental methodologies. The lab reports require standard sections such as: abstract, introduction, methods & data, analysis, and results & conclusions; we refer to them as “in-depth” to contrast with our previous short-answer post-lab format. Since the lab reports require much more work on the part of the students, we only implement six labs per semester. This reduction somewhat limited student exposure to traditional pieces of lab equipment. However, since the labs are not formulaic and encourage inventiveness, the students become very familiar with the equipment utilized.

The instructions for the inquiry-based lab challenges we have developed are:

• **Lab 1: Specific heat**

Your firm has been hired to design a steam heating system for the university’s new engineering building. Determine the identity of three separate cubes of different materials by devising an experiment to measure their specific heat values. You may choose which three cubes to study. After identification, compare the measured specific heats with their accepted values. Explain which material would be best for constructing the steam system’s pipe network.

• **Lab 2: Ideal gas law**

You are preparing for an interstellar voyage to Kepler-186f, an Earth-size planet 500 light-years away toward the Cygnus constellation. Your crew consists of an atmospheric scientist, a chemical engineer, a mechanical engineer, and an astronomer. Kepler-186f is in the “habitable zone” where water would be in its liquid phase. Once you reach Kepler-186f, your first task will be to characterize the atmosphere (find its molar mass). Your second task will be to calibrate the volume of your gurdyloo (a glass flask plus rubber tubing connected to a pressure sensor), a critical piece of equipment for further analyzing the atmosphere. Develop a strategy to complete these tasks. Practice these tasks here on Earth and compare to the expected values. Note: a gurdyloo will melt if exposed to liquid on Kepler-186f, but you may devise a liquid-based measurement on Earth for calibration.

• **Lab 3: Applied & induced charge distributions**

You sneak into Nicola Tesla’s museum after hours, and you come across a mysterious metal orb that is making a crackling sound. You want to know if this is a dangerous, highly charged object, so you fly back to Laramie to devise *two* safe ways to measure the charge on a metal ball. Quantitatively compare the consistency between the two values.

• **Lab 4: Capacitance**

You shipwreck on a coral reef next to an uninhabited island. Being the brilliant leader of the surviving group, you assert that a good way to flag down a passing ship is to run a large, brief current through some conducting filamentary wire to create a momentary but bright flash of light. You set out to construct some capacitors with the materials that washed ashore with you. First, construct three capacitors with paper dielectrics. Measure their capacitances and infer the paper’s dielectric constant in each case. Compare the estimated paper’s dielectric constant to accepted value(s). Second, place the capacitors in series and quantify how well the measured equivalent capacitance matches the expected value.

• **Lab 5: RC time constant**

You are hosting a Halloween party and need to hack into the mummy’s voicebox to make its sound spookier by making it fade more slowly. You decide to do this using an RC circuit. Devise a method to measure the resistance and capacitance RC for a DC circuit. Compare this to what is expected based on separately measuring R and C with a multimeter.

• **Lab 6: Magnetic fields**

During your interstellar voyage to Kepler-186f, one of your crew members smacks their noggin during a game of Pokémon Go gone horribly wrong. You quickly cobble together a simple MRI machine to assess the severity of the injury. Devise an apparatus that will generate magnetic fields of approximately 1.00 mT, 1.25 mT, and 1.50 mT. Compare your results to those expected from theoretical considerations given the physical properties of your apparatus.

The lab experience

In our inquiry-based environment, the lab procedure is shifted away from a series of repetitious measurements to primarily developing and improving a procedure to address a problem. These labs tie directly into the iterative engineering design process, which is particularly beneficial for our engineering students. This process is not explicitly taught but is experienced naturally through trial and error. One of the major challenges to developing inquiry-based labs is proposing a sufficiently difficult problem that students can still solve. In order to keep students from getting too frustrated during the critical thinking process, a large component of the instructor

and TA responsibility is careful guided assistance.

Each approximately two-hour lab has been constructed such that the main goal of the experiment is not getting a highly accurate result, but being engaged in the experimental process. After each lab, individual students submit an in-depth (three- to five-page) report of their process and the interpretation of the measurements they made (see the appendix¹³ for an example report). Students are expected to clearly demonstrate an understanding of their lab procedure, to the point that another student could replicate their experiment after reading the report. The students are expected to find the average percentage deviation from the expected value (the ‘error’) and to quantify the uncertainty on their result. With these goals in mind, students have to consider why repeated measurements are important and how many are necessary to produce a reliable result. Error and uncertainty are always a challenge for the students, and so we review these concepts and our expectations multiple times, both in the “lecture” component of the course and in short tutorial sessions with individual lab groups. These reports also give students an opportunity to reflect on their procedure and explain what improvements they might make if they repeated the experiment. The reports are graded not on the accuracy of the experiment, but on the clarity and quality of the written product and whether the student included all the required components explained in the rubric (abstract, methods, analysis, results, conclusions, etc.).

Student comments

In order to evaluate student attitudes towards these new labs, at the end of the semester all students were asked:

Do you think you learn more from the inquiry-based format adopted this semester, or from a more traditional format that provides more step-by-step guidance? Explain.

Nearly three-fourths (74%) of the students believed they learned more from inquiry-based instruction.

Comments in favor of the traditional route:

- “Step-by-step guidance helps me learn more. I feel like we spend a good 15 minutes chasing our tail, trying to figure out what to do.”
- “I tend to learn best when I’m shown how everything works and it’s pointed out to me how things work together so I can visualize and understand what’s going on.”

Comments in favor of inquiry-based:

- “I have learned more from labs in this class than I have from any other physics class. Not having a lab book with hoops to jump through unlocks the learning potential.”
- “I definitely learn more having to figure things out, but

I like doing it the traditional way better because it’s easier.”

- “Definitely the inquiry-based labs. Step-by-step is way too cookbook and it’s easy to go through an entire lab without knowing what’s happening.”
- “I learn more from inquiry-based, but it results in more errors.”
- “I think I learn more from inquiry-based labs because they feel less like busy-work.”
- “I’d say I learn more from the inquiry-based format, but when it comes to knowing exam material the traditional classes are less imposing.”
- “I think I learn more with this setup because you have to understand what you’re doing.”

Reflections

During the development and initial implementation of these labs, we learned many useful lessons. Despite initial trepidation about the time investment needed to produce each activity, the labs were in fact quite simple to write. Particularly for inquiry-based labs, it is paramount that the teaching staff is well prepared to provide thoughtful guidance. As part of our preparation, our entire instructional team worked through the experiment (and complementary theoretical aspects) together; during this practice session we pointed out to each other the potential pitfalls students may encounter. Moreover, it behooves the instructor to hire multiple lab assistants, including at the undergraduate level; ideally, there would be an instructor or TA for every two to three lab groups. Interactions between the students and instructors are vital to keeping students from getting too far off-track. To keep students on-track, we required them to have their experimental plan and theoretical interpretation signed off by an instructor. This signature was required before they were allowed to gather the necessary equipment from the nearby shelving (which typically included some red herrings). In our first two iterations of utilizing inquiry-based labs, we were limited to just the lead faculty member and two teaching assistants, which equated to one instructor for every four lab groups. In our view this was the bare minimum to accommodate the needs of the students.

Almost all of the approximately two hours reserved for lab was spent by students developing and revising their plans, with all necessary measurements often taking as little as five minutes to complete. The increased critical thinking time allowed for greater student ownership and creativity, and some of the greatest learning moments occurred as students refined their experimental plan. Sometimes students came up with novel experimental plans that were unanticipated by the instructional team during the practice run. If the instructors deemed a plan to be potentially viable, the students were allowed to proceed. The students developed a sense of pride when they devised methods their instructors had not

considered, and the lack of certainty in the final result made the classroom lab activity resemble a real experiment. If their experiment produced relatively large deviations from expectations (“errors”), the students were not faulted but they were required to address this in their lab reports and to explain how they could have improved their experimental plan.

Since the lab portion naturally flows from the lecture component of Studio Physics, there is no pre-assigned “lab day.” In this way instructors have the flexibility to delay the lab until they are confident all the necessary background material has been sufficiently covered. Moreover, students have an additional incentive to come to class every day, lest they miss lab. Excluding excused absences (e.g., illness or athletics commitments), our attendance has averaged over 95% for Studio Physics II.

The grading of lab reports required a large investment of resources. Although reducing the number of labs from 12 to 6 helped alleviate this pressure, about 20 minutes was spent grading each lab report. In addition, each week the lead faculty member graded approximately three lab reports in collaboration with the teaching assistant in charge of grading, to demonstrate the expectations for that week’s lab with respect to the grading rubric. Having students submit a group write-up would obviously cut down on the grading time, but would also reduce student practice with writing reports. Another option we are considering for future semesters is to introduce “Lab 0” at the beginning of the semester, where students are asked to grade an example lab report according to the rubric. The feedback to the student would be a copy of the same report graded in detail by the TA. This should help to more quickly familiarize students with lab report expectations.

Despite the increased time required to grade individual labs, reducing the number of labs made the overall time spent grading labs throughout the semester close to that for a traditional lab model. For a given lab the preparation time for TAs was also similar to that for traditional labs. However, since the TAs were physics students who typically enjoy problem solving, the TAs reported that the preparation for this type of lab was more enjoyable.

Acknowledgments

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