Best practice for instructional labs

Undergraduate labs are more effective and more positive for students if they encourage investigation and decision-making, not verification of textbook concepts.

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Physics is founded on both theory and experiment. Typical undergraduate curricula feature theory prominently, but experiment is featured only in labs (laboratory or practical components). Labs offer students glimpses of what it means to do experimental physics — glimpses that can be inspiring, repellent or anything in between. To ensure labs are inspiring, rather than repellent, we must consider the question, ‘What is the purpose of instructional labs?’ Nothing has made us consider this question more carefully than having to creatively adapt labs in response to the COVID-19 pandemic.

The motivation behind labs can be in service of theory, in service of experiment or some combination of the two. Here we present evidence from physics education research that suggests it is more effective for labs to be explicitly and exclusively in service of experiment, rather than in service of theory. Rather than using the experiments in a lab to demonstrate a particular theoretical model, labs should showcase what it means to do experimental physics: the approach, techniques, skills and ways of thinking when conducting authentic physics experiments. This focus is important not only for future scientists but also for citizens, to better equip them to interact with the complexity of the world and interpret scientific advancement in light of uncertainty.

When labs are used in service of theory, the purpose is typically to provide hands-on, real-world experience of theoretical models. Students generally expect that labs will have this purpose^{1–3}. Labs may achieve this aim by having students discover the models through their experiments or demonstrate models seen previously in lecture or the textbook. We refer to the latter as ‘verification labs’, which often use well-defined, structured experimental protocols so that students will necessarily verify the intended physics principles. For example, a verification lab may aim to reinforce students’ understanding of Hooke’s law by having them collect data of the extension of a spring with varied hanging masses to demonstrate that the force is proportional to the extension.

We and other researchers find that verification labs do not measurably add

to students’ understanding of the physical models they aim to verify^{4–6}. These studies find consistent results across a diverse set of institutions, from community colleges to private research universities. Let us reiterate this point: research indicates that instructional labs explicitly designed to improve students’ understanding of theoretical physics models do not measurably achieve this goal.

At the same time, verification labs also result in students expressing perceptions of experimental physics that are less aligned with those of expert experimental physicists than when they began the course^{5,7}. Many of these perceptions tie explicitly to the role of verification in lab activities. Students express beliefs that the goal of lab experiments is to verify theory^{1,8} or that experimental results should be primarily evaluated based on their agreement with theory^{5,9}. We have also found that these verification perceptions can emerge through students’ behaviours in the lab. Students’ explicit intent to verify theoretical models (such as in the quote in Box 1) leads them to engage in questionable research practices such as manipulating data, failing to seek disconfirmatory evidence or inflating error bars to obtain agreement with theory (such as in the quote in Box 2)⁸.

Concerns about verification labs are not new and most physicists would agree that verification labs do not represent authentic experimental physics. Many physicists have been advocating for and implementing instructional labs that remove structure and more realistically model the process of carrying out a physics experiment. Many instructors worry that this shift will sacrifice an important opportunity for students to connect the classroom theory to the real world. However, other instructional strategies, such as through lecture demonstrations and simulations, can substantially build students’ understanding of theoretical concepts while connecting to the real world.

Lecture demonstrations and verification labs both use physical equipment to demonstrate a physical model. However, the instructor, rather than the student, handles the equipment in a demonstration,

Box 1 | Student testing the period of a pendulum at different angles of amplitude explicitly seeks to verify the simplified model

“We will now try to be more precise by recording ten consecutive periods, so that the periods are more alike.”

so that the students can focus their attention towards learning the physics at hand, rather than worrying about how to handle the equipment and make measurements. Demonstrations can also be chosen and designed purposefully to address confusing and counterintuitive concepts and to reduce complexity. Research particularly advocates for having students first predict the outcome before seeing the demonstration^{10,11}. Researchers find that these demonstrations measurably add to students’ understanding of the physical models they aim to demonstrate¹¹.

Simulations are another form of instruction with goals in common with verification labs. Students interact with simulated equipment and physical phenomena with many extraneous variables controlled or hidden. Students can easily manipulate variables and engage in quick ‘trial and error’ investigations at their own pace¹². Simulations also have the benefit of demonstrating principles that are not easily observed in the real world. Research shows that student learning from computer simulations can be as good as or better^{13,14} than learning through hands-on activities.

The research does not say that labs cannot teach theory. However, the research does indicate that using labs in service of theory negatively impacts students’ understandings and perceptions of experimental physics. If you want to help students understand a physical model in a way that ties to the real world, use a lecture demonstration or a simulation. These methods reduce the complexity of the real world, while maintaining a connection to it. This leaves labs free to embrace the complexity.

Box 2 | Student explicitly inflates uncertainties to obtain agreement between measures and verify the simplified model

“Based on our [results], our values were possibly different. However, considering the unreasonably low uncertainty, it is believed that our values were probably not different. Therefore we tried using 0.02 seconds as our uncertainty. After doing so, our [test statistic] equalled 0.8367, which would prove that our values were probably not different.”

Lab environments have multiple features that are uniquely conducive to embracing the complexity of experimental physics. For example, the smaller teacher-to-student ratios that are typical of labs offer students more support in designing their own experiments and the long time blocks provide students with enough time to iterate and improve on their experimental methods and data analysis. Labs can provide students with access to equipment and technology, such as oscilloscopes, multimeters, analysis software and LabView.

Our research identifies two critical features for accomplishing these goals: (1) let students engage in the decision-making of experimental physics and (2) remove all verification goals.

For the first, allowing students to make decisions establishes a spirit of inquiry and provides deliberate practice with the cognitive activities associated with conducting an experiment. We are not advocating for removing all structure and handing all control over to the students. Learning requires structure. The structure should support students in making the decisions about how to conduct their experiment¹⁵. The structure should also support them to reflect on their decisions to learn how to make better decisions⁶. Periodically, the structure should be almost entirely removed: an opportunity for students to apply their newly acquired skills in an authentic context, similar to how a sports practice culminates in a game. For example, we design each of our labs to end with students conducting their own

experiment to answer a research question that emerged from their earlier results.

The second critical feature, removing all verification goals, helps students engage authentically. Our research has demonstrated that even a hint of a verification goal can lead students to engage in the questionable research practices described earlier¹⁶. Some labs have opted for using experiments with surprising outcomes^{17–19}, such as situations where canonical models break down. Thus, students design and test new models to explain the surprising observations, pushing beyond the material typically presented in the textbook. Others have opted for having students experiment to test a suite of possible models to explain a weird observation²⁰. Another approach has been to focus squarely on skills development, such as students’ understanding of uncertainty and measurement^{21–23}, communication skills^{19,24} or data analysis skills²⁵. Alternatively, allow students to ask the research questions (again, with structure) such that neither the student nor the instructor know the ‘right’ answer. In our favourite lab, we have students bring in stretchy objects from home to explore whether, how, when or the degree to which they obey Hooke’s law. We decided that the best, most authentic lab was one where the outcome could not be found on the Internet.

Physics education researchers have not yet tested which of these various approaches are ‘better’ than the others and ‘better’ will depend on the instructional goals and the institutional and course contexts. Researchers have tested how these various approaches compare with verification labs and repeatedly find that they improve students’ experimentation skills and perceptions of experimental physics (for example, refs. ^{5–7,17,18,20–23}).

It’s exciting to see many instructors are making innovative strides in transforming labs and integrating experimental physics into undergraduate physics curricula. Our hope is that others will be inspired to use the evidence from physics education research as they continue to negotiate the instructional demands of the COVID-19 pandemic and, importantly, when we return to ‘normal’. □

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Competing interests

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