Case study on how to develop 3D labs with theoretical, experimental, and computational goals

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Overhauling a laboratory experiment is a daunting process. Overhauling a whole laboratory course or curriculum is even more time consuming and terrifying. However, both endeavors can be very rewarding. Here I will show you the steps you can take to develop or overhaul the laboratory curriculum, course, or a single experiment so that it meets your goals. In our case, we wanted to update our courses so that our laboratories would be 3D with three different types of goals: theoretical, experimental, and computational.

I. INTRODUCTION

There is no better time to overhaul physics laboratory courses than right now. Recently, research has shown that laboratories that have goals of reinforcing course content have no value added when it comes to learning that content for the final exam [1]. Given the expense and effort required to mount a laboratory course, it is worthwhile to take the time to rethink courses with these goals and update them. After all, the laboratory is more than just a vehicle for course content; it is the method by which we teach future scientists to do science.

It is also a good time to update laboratory courses as the American Association of Physics Teachers (AAPT) has just published a new set of laboratory guidelines, which include learning outcomes in five focus areas: constructing knowledge, modeling, designing experiments, developing technical and practical laboratory skills, analyzing and visualizing data, and communicating physics [2]. Laboratory courses that want to implement best practices should be updated to meet these learning goals.

In addition, we need “3D laboratory courses” that integrate theoretical, experimental, and computational goals. That is, laboratory courses should not just cover the theoretical topics or just meet the experimental goals outlined in the AAPT laboratory guidelines. Instead, the laboratory should provide authentic experiences that mix theoretical, experimental, and computational learning outcomes. As the AAPT has just published computational guidelines that outline goals for how to construct knowledge using computational tools, computational physics skills, and technical skills [3], the time is ripe to update the laboratory.

However, updating the laboratory is an incredibly daunting task. Where should we start? How should we go about it?

Here I provide a roadmap that our department has used to update the laboratory for “3D” physics. For updating the curriculum and the courses in the curriculum, we used a four-step process: 1) identifying learning goals, 2) describing current practices, 3) making changes, and 4) planning for assessment. This process is based on others recommendations [4-8] and modified to suit our particular needs. To create 3D experiments, we modify existing training modules that are used in modern research laboratories. Using these processes, we are updating the laboratory with theoretical, experimental, and computational goals.

II. CURRICULUM OR COURSE

A. Identifying learning goals

The first step in updating the laboratory curriculum or course starts with identifying the learning goals for students. These are the things that you want students to be able to do or know at the end of the course. The reason for starting with these goals is twofold. First, when designing the curriculum or course, you need these goals to guide the changes you will make. Second, most instructors will be able to agree on the goals [6], making it a great place to start.

More specifically, one of your first objectives is to get buy-in from the faculty and staff that teach the course on the changes you will make. The easiest way to get buy-in is to involve everyone from the beginning in the process. At our small college, we have at least five people that should be included in laboratory discussions, but at large institutions there may be more. How do you get everyone on the same page? The key is to start with the learning goals, since this is an easy place to sow harmony.

To identify curricular goals for our laboratory sequence, we held one meeting where all interested parties could attend. Before the meeting, everyone was given a copy of the AAPT laboratory guidelines and the AAPT computational guidelines. This facilitated the discussion during the meeting as almost everyone agreed on the goals in these documents. In addition, the purpose for the meeting—to update the laboratory sequence to meet theoretical, experimental, and computational goals—was clearly outlined. This purpose allowed our group to stay focused on these three types of goals and complete the task in just one hour. Finally, during the meeting we tried to keep the goals broad, rather than specific. This allowed us to list all of the goals easily without too much discussion. For a list of the goals we came up with see the “Goals and practices - curriculum” document.

To identify goals for each course, we used the same strategy. We gathered the instructors that had a stake in each course and sat down for a one hour meeting to define the course goals. We found that there was almost perfect overlap between our course goals and our curricular goals.

This overlap is most likely because the goals in the AAPT laboratory guidelines and the AAPT computational guidelines documents are so broad. For example, one of the goals is to “analyze and display data using statistical methods” [2]. This is definitely a goal for the curriculum and for each of our four courses in our laboratory sequence. However, the degree of sophistication in each of the courses is different. Analyzing and displaying data in an introductory lab course may just involve plotting a line, while in an advanced course it may involve plotting a Poisson distribution and the residuals. Thus, the goals for each course are the same, but the actual practices in the different courses are different.

B. Describing current practices

The second step in updating the laboratory curriculum or course is for your group to describe the current practice in the department. This should be an easy step since your group just needs to recall what happened in the course or courses the last time they were taught. This step not only moves things along, but also increases agreement among the group.

We accomplished this task in a one hour meeting by creating a single document that described the practices in our department, see the “Goals and practices - curriculum” document. In this document, we listed the four courses in our laboratory sequence along the top. Then, we placed the goals for the course along the side, creating a grid. At each location in the grid, we listed the practice in that course for meeting the goal. For example, if the goal was for students to be able “to process and represent data” using technical computing skills [3], then in the introductory lab our current practice is to tell students exactly how to process and represent the data in the laboratory directions. Whereas, in the advanced lab the current practice is to have students decide what data to take, how to process it, and what representation to choose. Each one of these practices is added to the grid at the correct location. To make the document more useful, we grouped the goals into the three categories of theoretical, experimental, and computational. This grid allowed us to see the current practices in each course at a glance.

C. Making changes

In the third step of the process you will want to assess your goals and current practices and decide on changes. This involved another one hour meeting of the group.

First, we looked at the empty grid squares in our “Goals and practices - curriculum” document. An empty grid square means that there are no current practices in the course that help students meet that goal. Sometimes this is by design. For example, troubleshooting is an experimental goal for our courses, yet in the introductory lab we keep troubleshooting to a minimum due to time constraints. Other times, the grid squares are empty because we have not been meeting our goals, or we have identified a new goal for the course. In these cases, we filled the empty grid squares with practices that we would like to implement.

Second, we looked at adding practices. Sometimes there were not enough practices to meet a particular goal. For example, in the computational goals section in “use a mathematical/computational model to represent reality” we had two courses that gave students the model and then asked them to verify the model with their data. In a third course, we had the students come up with a model and refine it. To bridge these courses, we added practices to the introductory lab of giving them part of the model or having them come up with a model and refine. Adding these practices allowed us to scaffold the students from one lab to the next.

Third, when adding practices or even describing current practices we made sure to note alternatives. There are many ways to achieve a particular goal and one method might work well for one instructor and not for another. To be inclusive of these alternate methods, we wrote them all down. For example, there were many different practices that instructors wanted to implement to improve student communication skills. Our traditional method is to require three written lab reports. However, some instructors wanted to try scaffolded reports [9], oral presentations, or executive summaries. Rather than discuss all of the methods, we just list them all as alternatives.

Fourth, we did not remove practices; we only added practices and listed alternatives. This document is supposed to represent current practice in the department. If next year, the practices have changed because faculty have updated their practices, then the document will shift naturally. This allows instructors to make changes at their own pace.

D. Planning for assessment

The last step in the process is to plan for assessment of the curriculum or course. Assessment is needed so that you know how to update the course.

While it is possible to use nationally recognized surveys [7] or practical evaluations [10] as laboratory assessment tools, our current practice is to use course evaluations, see the "Course evaluation" document for more details. Using this assessment, we are able to rank how we are doing at each goal and continuously update the laboratory.

III. EXPERIMENT

While the overall planning of the course or the curriculum requires a group of people, the nitty-gritty planning of the actual experiment usually falls to one or two people. How then should these lucky souls go about updating or creating a particular experiment?

One traditional method is to give the current instructor of the course the job of updating or creating particular experiments as they teach the course. This then leaves it to the instructor to complete the four-step process outlined in the introduction. Given the time it takes to update experiments, this policy usually means that the laboratory is rarely updated.

Another method is for the department to identify a "task force" of two or more people to update or create experiments using the four-step process. This is a favorite method in our department for creating experiments for new laboratory courses. The beauty of this method is that the laboratory is updated since the task force has to report back to the body that empowered it. The limitation of this method is that it is rare for a task force to even be created.

Another method is to have a national repository of modular experiments that are easy to insert into laboratories. This works well if a physics education company takes the lead to build these experiments, or if instructors publish their experiments in physics education journals and sign up to teach other instructors in immersive experiences [11].

However, these modular experiments need to be "plug and play". "Plug" here means that each experiment is stand-alone so that it can be plugged into a course. However, to be easily plugged into a course, the experiment itself must not require any other experiments, and it must cover all of the theoretical, experimental, and computational goals of the course. This allows the instructor to plug the experiment into the course and choose the particular goals that will be emphasized. "Play" here means that the experiment can be played during a single three hour time slot or over multiple weeks. This allows the instructor to tailor the experiment to the course. Instructors can then choose from a set of these plug and play experiments to build a laboratory.

It might sound impossible to create an experiment with theoretical, experimental, and computational goals that can be dropped into a three hour laboratory or extended for multiple weeks. However, the experiments students complete in a modern research laboratory are already fulfilling most of these goals. Breaking these research experiments into manageable chunks for a course provides not only an authentic training for students, but gives instructors the freedom to emphasize different goals. Here I will discuss how to adapt research experiments for use as plug-and-play, 3D classroom experiments using two examples.

A. Identifying research experiments for adaptation

To identify research experiments that would work as classroom laboratories, you want to constrain yourself to research experiments that cover topics of interest and to research experiments that lend themselves to manageable training exercises.

I was interested in biophysics experiments so naturally levitated towards a Brownian motion experiment. Brownian motion is the random movement of micron or submicron objects in a liquid and is incredibly important in molecular biophysics. It is involved in ion transport, in the movement of lipid molecules, in transport of molecules or organelles within the cell, and many other cellular processes. Modern research laboratories often fluorescently label molecules undergoing Brownian motion, including molecular motors, DNA remodelers, and cytoskeletal filaments, to measure their movements. To transition students into these research groups, there is often a first training experiment where the student tracks the Brownian motion of an object. In addition, classroom experiments on measuring the Brownian motion of micron-sized beads in water already exist [12].

Another experiment of interest for me was looking at the polymer properties of DNA. Polymers are ubiquitous in molecular biophysics in the form of proteins, nucleic acids, and cytoskeletal filaments. Polymer properties are necessary in understanding modern research on how proteins or nucleic acids fold or assemble and much of this modern research uses atomic force microscopes (AFMs) to visualize polymers, with imaging of single DNA molecules as a typical training exercise. In addition, this training exercise has already been fit into a classroom experiment [13]. All that is left to do is to outfit the experiment to be plug and play.

B. Outfitting the experiments as plug and play

To outfit the experiments as plug-and-play, 3D experiments, we need to identify the practices in the experiment that would meet the theoretical, experimental, and computational goals that we identified for our courses and our curriculum. This can be done by filling out the "Goals and practices – curriculum" document for just a single experiment.

Once the goals and practices have been identified, the experiment needs to be written so that as many practices as possible are optional. These options will allow individual instructors to tailor the experiment for their course. Options could include pre- or post-experiment exercises, methods that can be done by the instructor ahead of time, extra data or analysis sections, or alternative experiments. One important option might be a section on how the experiment could be outfitted for open-ended projects, increasing multi-week exploration. Each option should also be labeled with the goals that are covered in the option. In this way, the experiment is modular allowing for plug and play.

IV. CONCLUSIONS

Here we describe a four-step process for updating the laboratory curriculum or courses to be 3D, which includes goals that are theoretical, experimental, and computational. In addition, we describe the process for updating an experiment so that it is plug and play, allowing instructors to easily plug it into their 3D laboratory courses.

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[1] N. G. Holmes, et al., Phys. Rev. PER **13**, 1 (2017).
[2] J. Kozminski, et al., AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum. (2014).
[3] E. Behringer, et al., AAPT Recommendations for Computational Physics in the Undergraduate Physics Curriculum. (2016).
[4] M. D. Caballero and S. J. Pollock, Amer. J. Phys. **82**, 3 (2014).
[5] S. V. Chasteen and S. J. Pollock, AIP Conf. Proc. **1064**, 1 (2008).
[6] R. E. Pepper, et al., AIP Conf. Proc. **1413**, 1 (2012).
[7] B. M. Zwickl, et al., Amer. J. Phys. **81**, 1 (2013).
[8] B. M. Zwickl, et al., Amer. J. Phys. **82**, 9 (2014).
[9] L. J. Deiner, et al., J. Chem. Ed. **89**, 12 (2012).
[10] M. Finegold and J. Meyer, Stud. Educ. Eval. **11**, 3 (1985).
[11] https://www.advlab.org/immersions.html. Retrieved 7/6/2018.
[12] M. A. Catipovic, et al., Amer. J. Phys. **81**, 7 (2013).
[13] L. M. Devenica, et al., Am. J. Phys. **84**, 4 (2016).