Think first, act later - A course structure for improving student designed experiments

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There is a natural tendency for students to act first (e.*g.* - build and conduct experiments) and think later (*e.g.* - outline goals, identify challenges, predict outcomes, etc.). This is often apparent in labs that include student design components. We have developed a lab course structure that teaches students how to develop their ideas and make plans before beginning an experiment by providing multiple opportunities for peer and instructor feedback. As a result, we have seen significant improvements in the success rate and quality of student-designed experiments and presentations. We provide a detailed explanation of the course structure and rubrics and evidence of the impacts of this course structure.

I. Introduction

The sophomore and junior-level laboratory courses at Brigham Young University have two overarching goals; prepare students to complete a thesis project and to become capable experimentalists. To accomplish these goals, we have recently refocused our lab courses on teaching experimental skills and habits, such as those outlined by Wieman [1] and by the AAPT Committee on Laboratories [2], which go beyond a prescribed set of technologies, concepts, and/or techniques. In particular, our final lab course aims to teach students how to develop research goals, define criteria, and assess feasibility. A student design approach provides the best opportunity for accomplishing each of these goals [3, 4], but effective methods for student designed labs have not been fully explored. We discuss a novel approach to student designed labs aimed at helping students develop their ideas and make plans before the execution phase of a project while providing students a more authentic view of experimental research.

In this paper, we will describe our efforts to increase students' understanding of, and ability to conceive and develop, a research project. We provide a brief description of the course. We then describe how we have restructured the course to teach students to develop ideas. The new structure includes a final project composed of multiple assignments that are interspersed throughout the semester. It also includes day-long expansion projects and pre-course exercises to provide practice and feedback to students throughout the semester. We conclude with a discussion of some informal, qualitative impacts observed from these changes.

II. Course Background

The course discussed here is intended to be the last lab course students (first and second semester juniors) take before they begin seriously working on their undergraduate thesis research. Since most students will not have a significant role in defining goals in their research groups, we feel it is important to provide them with a meaningful opportunity to practice setting goals and developing their ideas. To accomplish this aim, we began requiring teams of two students to conceive of, design, and implement an experimental investigation during the final three weeks of the semester (a total of six, 3-hour lab periods).

In early attempts to include a final project, we observed certain aspects of the assignment that students struggled with which had a negative impact on overall success rates. First, students struggled to conceive of a project. This is not surprising considering how few opportunities they have had to set the goals and scope of a project. Whether from procrastination or self-doubt, delays in deciding on a project reduced the amount of time spent on developing the idea. The result was often a final project with a poorly defined scope. Second, once a project was selected, students quickly proceed to the execution phase of the experiment without allotting appropriate time and effort to assess feasibility and to determine the criteria for success. Again, this is not surprising considering how many well-defined and procedural problems they have faced throughout their academic careers. We noted the same ineffective approach in student-designed projects completed earlier in the course. Third, students failed to make a detailed plan with the necessary steps, including contingencies, required to successfully complete their project. Fourth, students struggled to manage time and schedule resources. As a result, precious time was wasted duplicating efforts and waiting on resources.

III. Restructured Final Project

To alleviate some of these problems, we restructured the final project into three distinct parts, interspersed throughout the semester. The three parts, described below, are a white paper, a full proposal, and execution and presentation of results. Typical feedback we provide at each step is described below. While restructuring the final project is our main focus here, other noteworthy changes to the course are discussed in section IV.

A. White Paper

The first milestone for the project is the submission of a white paper by each student in the class. We define the white paper as a report on a complex project that the student would like to investigate. It acts as a sort of pre-proposal and focuses on describing the background and potential benefits of the project as well as the techniques and technologies required to successfully complete it. Some examples of white papers that were developed into successful projects include, measurement of the Verdet constant of water, construction of a Fabry-Perot interferometer to measure the mode of a diode laser, and design and construction of a Paul trap.

The method for reviewing the paper is as important as its preparation. Each semester it is taught, the class has two sections. After anonymizing the submissions, the papers from each section are reviewed by several students in the other section of the class. Each student in the class is assigned three papers to review. In addition, they are responsible for presenting and leading a class discussion on one of those papers during the panel review discussed below. As they review the papers, students consider whether the experiment would be interesting, whether it is relevant to the research areas covered in the class, and whether it seems like a feasible project can be developed. Interest and relevance seem to be well understood by the students. To help clarify how to assess whether a project is feasible, students are given three criteria: (1) Has a calculated prediction been made and do the results indicate that the measurement can be made? (2) Is the equipment necessary for such a measurement available and, if not, has the student indicated how they plan to obtain any special equipment? (3) Does the clarity and completeness, including relevant references, indicate that the student understands the project well enough to complete it? They are also asked to rank each proposal against the others they have read and provide their opinion on whether they think the project should go forward.

After reviewing the papers, one 3-hour lab period is dedicated to presenting and then discussing each paper. Students take the lead on facilitating the discussion while the instructor takes notes to give as feedback to the author. On occasion, the instructor may contribute questions and comments to model how the discussions should proceed. At the end of the discussion, students vote on each of the categories (*i.e.* – interesting, relevant, feasible) for each paper and after all papers have been presented the class decides which projects will be "funded" or allowed to proceed. Scoring and comments about each paper are recorded and returned by the professor to the author as feedback.

The introduction of this milestone provides a clear distinction between the goal of the project and the detailed proposal of how it will be accomplished. In addition, the review process provides each student with an opportunity to learn how to critique experimental concepts from the perspective of a reviewer and introduces them to the important paneling process they will engage in as professionals.

This process has a significant impact on how the students view their own ideas. As an example of this, at the end of the review session but before getting their own comments back from reviewers, we ask the students if, after having reviewed the other section's whitepapers, they wish they could rewrite their own whitepapers. Their response is almost always unanimously in the affirmative.

B. Full proposal

Only 50% of the white paper proposals are "funded". Students with successful papers are joined by a student in the class whose project was not funded and the two work to develop a full proposal. Since the white paper is submitted early in the semester, the students have plenty of time to develop their ideas and tune their proposals based on feedback from the review process. All comments from the whitepaper review are expected to be addressed in the full proposal.

Before submitting the full proposal, each team prepares an oral presentation on their project which they deliver to their own section. This gives the team a chance to get feedback from their peers, teaching assistants, and professors before turning in their full proposal. In order to help the students work as equal partners, both students work together to prepare the oral presentation but the student which did not write the original whitepaper on the project is required to deliver the presentation and field any questions.

Shortly after the oral presentations, the full proposals are submitted. As with the whitepapers, these are anonymously reviewed in a panel discussion by the other section. Comments from this discussion are sent to the students. Again, the students are expected to revise their proposal to address these comments before turning the final proposal in a second time for review by the professor. The multiple iterations of feedback and revision are a necessary part of learning to successfully develop ideas as a professional.

C. Execution and oral presentation

Once the team has addressed all remaining concerns about their proposal, they can begin executing their plan. While the last six lab days are reserved for the projects, the most successful teams will be assembling parts well in advance so that there will be no delays. However, accommodations are granted for unforeseen issues. Teams work independently but have many opportunities to get feedback and assistance from TAs and the instructor throughout the process.

At the conclusion of the project, students prepare and deliver an oral presentation of their results as the class final exam. The final presentations are conducted in the same way they would be at a conference except that both members of the team are expected to deliver slides and respond to questions. The presentation is peer reviewed to provide constructive feedback. Students must attend their fellow students' presentations and are expected to ask questions of the presenters. In addition, the presentation is graded by the instructor and serves as the final exam for the course. Students learn the rubric for the presentation earlier in the semester as they give presentations on the smaller expansion projects described in section IV. The rubric includes organization of the presentation, understanding of the material, delivery, and quality of the slides.

IV. Expansion projects and pre-lab exercises

In addition to changing how students prepare for and execute their term project, we made several changes to the course to improve how students approach original research and to help them be more successful with their term project. One of the changes was to make the labs more open ended. The labs in this course cover the topics of vacuum systems, acoustics, microfabrication, and optics. While some of our labs, of necessity, have expected outcomes, many of them have been altered to allow the students creative license in what experiments to perform. Most of the labs now allow students to choose their own approach to achieve results. In addition, some labs only provide a task to complete without any instruction. After giving students a short time to investigate, a class discussion is held to allow each team to share what things they tried and what they found.

Twice during the semester, we also dedicated three of the 3-hour lab periods to "expansion projects," which are essentially mini-term projects. During one lab period students come up with an experiment that is an extension of or uses techniques learned in the previous experiments they have done in the class. They make predictions, design, build, and execute the experiments, and then analyze their data. The students prepare and present oral presentations on each of these expansion projects. The oral presentations are not graded, but their peers, teaching assistants, and the professor give feedback on their experiment and their presentation using the same rubric used to grade their final presentations. Two examples of expansion projects include the measurement of the Paschen Curve for various gases and using an optical interferometer to measure transparent objects.

Finally, we have also modified the pre-class exercises to help promote improved thinking and planning before an experiment. In addition to helping the students prepare for the technologies and techniques which will be used in each class period, we have added questions to help them think about how to design the day's experiment and be prepared to carry it out. For example, most of the pre-class exercises start with a question asking them to come up with three things they should look up or calculate before beginning to design and assemble the experiment. Each of these changes support the final project and help students practice the habit of developing ideas before implementing plans.

V. Discussion

As with any changes to a course, there are trade-offs to implementing this structure. Allotting time for presentations and proposal reviews naturally reduces the number of experiments that can be performed during the semester. While we have not measured the impacts of these changes, we have observed qualitative evidence of its effect during the three semesters that we have implemented them and feel that the benefits, with little to no increase in work load, make it a worthwhile trade-off. During this time, two sections of the course were taught per semester with a typical enrollment of about 8-10 students per section. Students expressed a positive view of the course structure. We found the course structure to be extremely effective at motivating students and inspiring ownership of the project. Interestingly, the ownership appeared to have little to do with the grade. One clear evidence of this is that students often continue working on their projects outside of lab hours. On one occasion, the instructor had lost track of time in the lab room working on other tasks and the TAs approached him to ask what they should do. The class period had already been over for a half hour and the TA needed to leave, but the students wanted to continue working. Several student teams have also been willing and at times eager to continue their projects after the close of the semester and three teams have even presented their work at a department colloquium. Ownership also did not seem to depend on who proposed the original project.

We also found that the students' ability to define a reasonable scope for their project has noticeably improved. This has led to a higher percentage of projects which are both interesting and successful. It is not clear whether the students will be equally successful at completing independent projects as a result of the class, but they have at least observed the benefits of practicing effective experimental habits.

Students have also commented that they have learned more about scientific writing in the class than they have in any other class. While no formal academic writing is required, the course structure helps students understand what aspects of a scientific communication, whether a proposal, report, or otherwise, will be important to the audience.

VI. Conclusions

In conclusion, we have described a new lab course structure designed to help students conceive of and develop experimental ideas. Structural elements of the course include open-ended lab activities, student-designed "expansion" projects, and a project proposal process. Each of these structural elements contribute to the success of a culminating student-designed final project. The open-ended lab activities provide students with an opportunity to practice and see the benefits of determining criteria and assessing feasibility before designing and executing a project. They also allow students to develop technical skills and knowledge that act as a toolbox for completing self-designed projects, such as expansion projects. Expansion projects, carried out twice during the semester, allow students to use their existing toolbox to investigate new ideas. These projects are shorter in duration and less challenging than the final project but are an important opportunity for students to recognize the unexpected difficulties that can arise during the execution of an experiment and thus promote better planning. After each expansion project, students present their work and get an opportunity to receive feedback on their presentations. By interspersing aspects of the final project proposal process throughout the course and providing multiple opportunities for feedback, we help set the students up for success. Having students be a part of the review process also allows them to consider scientific communication from the viewpoint of the audience. We feel that this structure is particularly useful for labs that include a student-designed final project and intend to measure the effects of this course structure on project ownership and attitudes toward experimental physics.

References

[1] Carl Wieman, The Physics Teacher **53**, 349-351 (2015).

[2] AAPT Committee on Laboratories, *AAPT Recommendations for the Undergraduate Laboratory Curriculum* (AAPT, College Park, MD, 2014).

[3] N. G. Holmes, C. E. Wieman, Phys. Rev. Phys. Educ. Res. **12,** 020132 (2016).

[4] N. G. Holmes, C. E. Wieman, Physics Today **71**, 38 (2018).