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A Study on Enhancing Advanced Physics Laboratory Teaching

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Introductory physics laboratory (IPL) courses are designed to educate students on general physics topics, but they lack the experimental sophistication and experience required for their future. On the other hand, diverse and high-quality advanced physics lab courses must be made available to prepare students for future careers and advanced degrees. In a recent AIP report, *Equipping Physics Majors for the STEM Workforce*, the report's first aim was "Varied and high-quality lab courses." With this in mind, an Advanced Physics Laboratory (APL) course for upper division students should provide the following.

- Physical aspects – access to a wide variety of instruments, experience in general problem solving and troubleshooting, collection of precise data, recognize experimental errors.
- Intellectual aspects – explore practical physics concepts, reduce and analyze data, utilize teamwork, communicate results in writing.

These aspects are crucial, as they are highly valued by employers. The first part of the course was dedicated to covering some important concepts of physics relevant to the experiments. The remainder of the semester contained experiments covering a wide range, including acoustics, optics, magnetism and semiconductors. At the end of the semester, an independent student survey was conducted to evaluate the students' perception of the course.

I. Introduction

It is not unusual for students to feel that the physics presented in textbooks and lectures is difficult to understand, making the subject their first enemy in school. A natural reaction is then to avoid many details of physics, or study simply for the sake of just getting through it and earning credits. Generally, this problem is enhanced by a lack of useful experimental facilities. In teaching physics, it is important to not simply memorize physics theories and laws or study physics from an exam point of view. Physics is not an alien language, it is a natural and experimental science that is visible all around us. Effective science teachers often look for simplicity to explain the behaviors in nature, since at first sight they appear to be messy. For example, Richard Feynman was famous for persuading scientists and mathematicians to explain complex ideas using only simple terminology. This can also be extended to the connection between theory and experiment. Robert Millikan stated "The fact that science walks forward on two feet, namely theory and experiment……."[1] Although the understanding of physics may start from theoretical concepts explained in the lecture room, those ideas when complemented with laboratory experiments reveal the simple truths via observations and analysis. Physics is *experiential*.

Indeed, experiments in the Advanced Physics Lab (APL) are different from those in the introductory physics lab (IPL). APL experiments should be carefully designed to go beyond the simple demonstration of fundamental physical concepts and must be explored by in-depth data analysis and scientific documentation. In the lab, students are advised in advance to prepare themselves to be frustrated at several stages throughout these experiments, since they are closer to reality without assumptions introduced in theory classes. The learning goals of this APL course were grouped into categories. These are in line with the AIP report, *Equipping Physics Majors for the STEM Workforce*, which stresses "varied and high-quality lab courses." [2]

- Select experiments with a wide variety of apparatus for varied applications
- Allow students to become intimately familiar with each scientific apparatus
- Gain experience with troubleshooting problems and look for sources of errors
- Record precise as well as accurate data, determine uncertainties in both measured and calculated values
- Observe and discuss deviations between initial expectation from theory and reality in experimental systems
- Allow students to practice working in groups
- Provide students with repetitive feedback on written scientific reports

Seven experiments were available [3]. The students performed six of the seven experiments by exchanging workspace positions for every experiment.

1. Acoustics and Fourier Transformation (AFT)
2. Coupled Electrical Oscillator (CEO)
3. Faraday Rotation (FR)
4. Fuel Cell and Solar Cell (FUEL)
5. Hall Effect (HALL)
6. Ruby Spectroscopy (RUBY)
7. Speed of Light (SOL)

All seven experiments are significantly different and incorporate acoustics, optics, magnetism and semiconductor physics. The AFT experiment, a student favorite, was designed to demonstrate the harmonic series of musical instruments (timbre), beats, interference and FFT conversion from time to frequency space. Some students brought in their own, and often unusual, musical instruments to record and analyze their harmonics. The CEO experiment was designed to stimulate their thoughts about mechanical and electrical oscillations and their energy transformations. The FR and RUBY experiments were more sophisticated experiments in terms of optical bench arrangements and data recording. The FUEL experiment exposes students to light/electrical/chemical energy conversion efficiencies, along with learning about the principles of a solar cell and a hydrogen fuel cell. It is worthy to note that the HALL experiment was designed to also give them practice on soldering wires onto a piece of semiconductor, as well as to understand the Hall effect and its application in semiconductor technology. Although many of the experiments were introduced as simple cookbook recipes, students were encouraged to provoke via their thought process by asking questions like “why is that happening,” “what happens if I do this,” “how can we improve the experiments and data collection?”, etc.

During the last day of the course, a survey was carried out to measure the following.

- How well our proposed learning goals were achieved, as judged by the students.
- How can we improve this course?
- Which experiments provide more stimulation, thus making them more enjoyable.

II. Laboratory Teaching Approach

The class was divided into groups of two students for each experiment. The first week of the course was dedicated to covering some important concepts of physics relevant to the experiments. While conducting the experiments the students were required to ***plot as they take data***, typically after every three data points, in order to decide where to take the next few data points. Upon completion of each section of an experiment, interactive discussions were employed between students and the instructors. This step-by-step method of checking the students' progress at each section was found to allow students to discover errors quickly, giving them indispensable ***troubleshooting*** experience. Concurrently, a weekly take-home quiz was given to stimulate their thoughts outside the lab environment through external resources. Students were also requested to maintain a laboratory notebook throughout the course as their personal academic diary with necessary information. At the end of each experiment, students obtained a signature from their teaching assistant on their raw data before they started working on their formal report. Students were required to submit a complete printed formal lab report within 4 days. The reports were not only graded, but were also edited in order to give them feedback before writing the next lab report. This sequential feedback led to significant and gradual improvement in their formal scientific writing.

III. Survey Analysis

The survey given at the end of the course had four main sections: *Learning Goals*, *Teaching Methods*, *General Feedback* and *Experiments*.

In *Section-1: Learning Goals*, students were requested to rate the following four learning goal statements between 1 and 5 (1-Low and 5-High).

Section-1: Learning Goals

1. I have become intimately familiar with each apparatus used in the lab in order to collect precise as well as accurate data.
2. I have understood the techniques for determining the uncertainties in both measured and final values.
3. I have gained real-life valuable experience in troubleshooting the equipment or setup via finding my own solutions to problems.
4. I have mastered the scientific methods of experimental documentation.

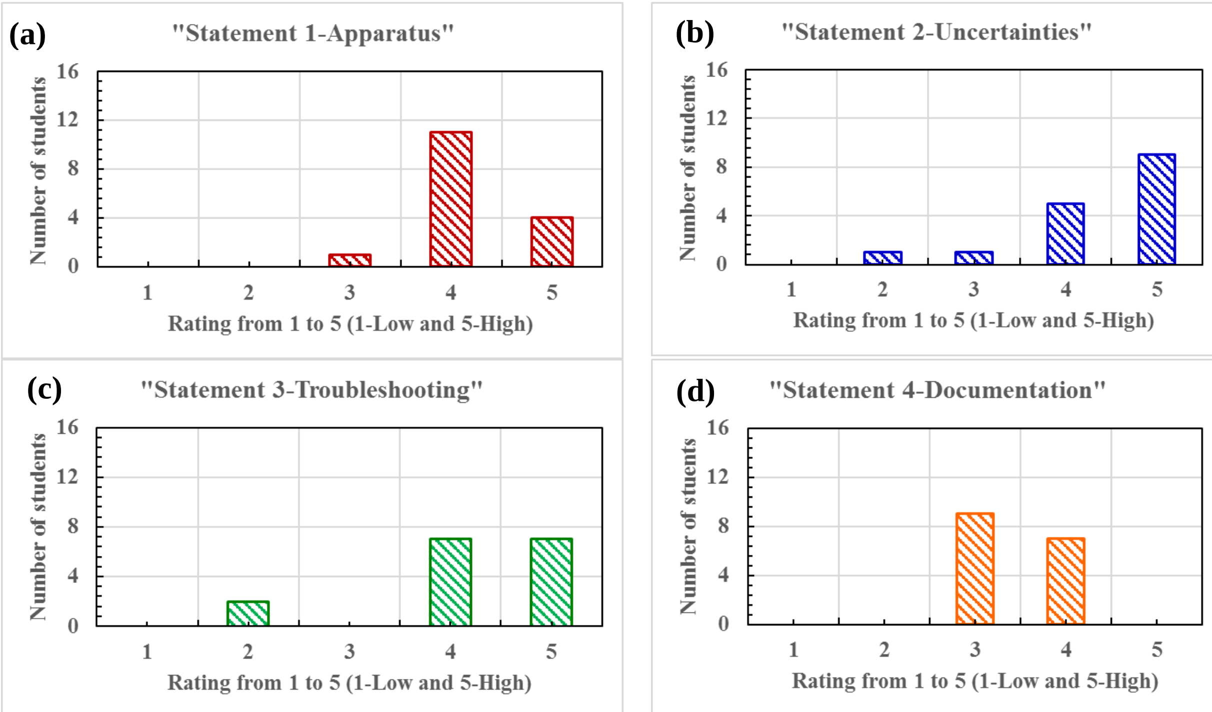

Figure 1: *Results of survey for the first four statements outlined in Section-1: Learning Goals.*

Figure 1(a-d) shows the outcome of the questions in *Section-1: Learning Goals*. Statement 1 (Fig: 1a), received the ratings of 4 and 5 by 69% and 25% of the students, respectively. Statement 2 (Fig: 1b), received the ratings of 4 and 5 by 31% and 56% of the students, respectively. Statement 3 (Fig: 1c), rated as 4 and 5 by 44% of the students. Finally, statement 4 (Fig: 1d) was rated as 3 and 4 by 56% and 44% of students, respectively. Unfortunately, none of the students rated 5 for this statement. This is an acceptable fact since our expectation was to see a significant and gradual improvement in their formal scientific report presentation compared to their first and last reports.

Section-2: Teaching Methods

In *Section-2: Teaching Methods*, students were instructed to circle one of the numbers between 1 and 5, where 5-Strongly agree, 4-Agree, 3-Neutral, 2-Disagree and 1-Strongly disagree.

1. The first week introductory lecture helped me to ***understand*** or ***revisit*** the physics concepts in advance before the laboratory (5 / 4 / 3 / 2 / 1).
2. The lab instructions guided me well throughout the experiments (5 / 4 / 3 / 2 / 1).
3. The class was very interactive in terms of helpful discussions between me and the teaching assistant/instructor/lab partner/fellow student (5 / 4 / 3 / 2 / 1).
4. When comparing my first and last lab report, I have seen very good improvement in my scientific report writing skills (5 / 4 / 3 / 2 / 1).
5. The take-home quiz questions stimulated my thought outside the lab via books and internet searches (5 / 4 / 3 / 2 / 1).

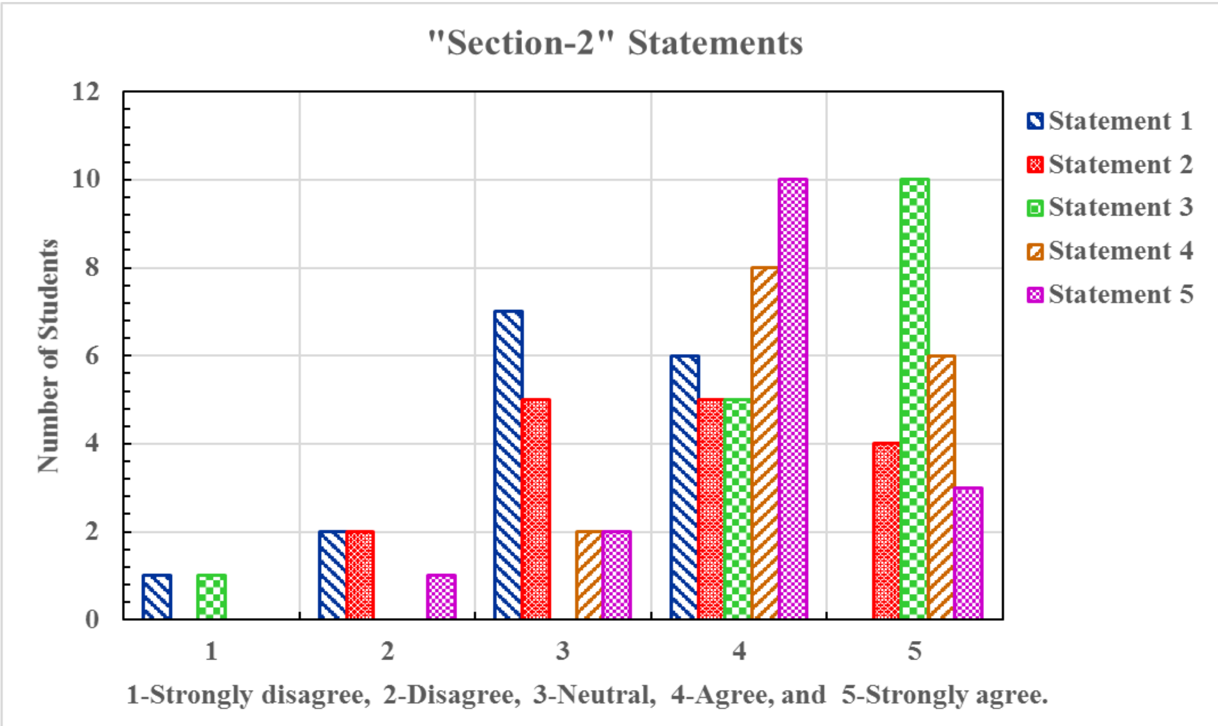

Figure 2: *Depicts the survey results for the first five statements outlined in Section-2: Teaching Methods.*

Statements in *Section-2: Teaching Methods* were generated with the purpose of identifying students' perspectives on the course structure in order to design a more enjoyable and self-motivated laboratory environment. When the lab environment is enjoyable, learning is accelerated. In Fig. 2 on statement 1, 44% of students were neutral and 38% agreed that the lectures were useful. This could signal that more demonstrations would be helpful. On statement 2, while 25% of the students strongly agreed on the usefulness of the lab instructions, 31% equally mentioned as agree or neutral. This somewhat reflects our objective of having minimal "recipe" instructions that require significant student attention. Statement 3 on interactive learning and discussions during the lab, students strongly agreed and agreed by 63% and 31%, respectively. Indeed, this is great news. For statement 4, 38% of students responded as strongly agree and 50% of students as agree about their improvements in scientific report writing skills when comparing their first and last formal reports. This response was very encouraging. Finally, regarding the take home quizzes in statement 5, 63% of students were agreed and 19% strongly agreed that these quizzes stimulated their thought process outside the laboratory environment via external resources.

Overall, students' feedback was more favorable for the current APL course structure with a minor amount of introductory lectures. None of the students strongly agreed with statement 1, indicating that we need to improve the introductory lectures, perhaps by including more demonstrations.

Section-3: General Feedback

In *Section-3: General Feedback*, there were two choices, “YES” and “NO”, to voice their opinions for the following statements.

1. I would like to have a closed book quiz in the class room rather than a take home quiz (Yes / No).
2. I found this course very useful in order to prepare myself for employment or graduate research laboratory in the future (Yes / No).
3. I will recommend this course to another student (Yes / No).

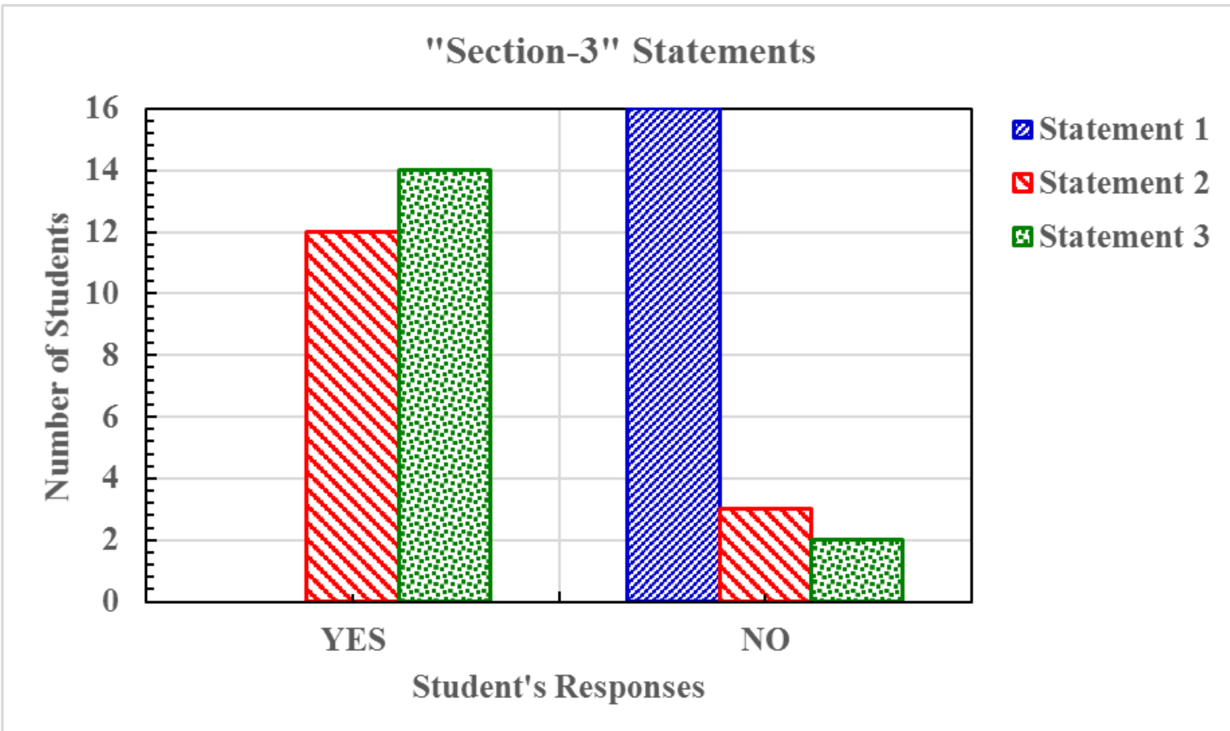

Figure 3: *Exhibits the survey results for the first three statements outlined in Section-3: General Feedback.*

Figure 3 shows the survey results for *Section-3: General Feedback*. None of the students voted as *“*YES*”* for a closed book quiz in the lab, as one might expect. It is not reasonable to measure a student’s knowledge based on their performance in a 15-30 minute closed book quiz. It is also worthwhile to note that in *Section-2*, 82% of students accepted that these take-home quizzes stimulated their thought process outside the laboratory environment via external resources. As instructors for the APL course, one of the goals is to encourage students to “learn as much as possible” during the course period. It is also encouraging to hear from statement 2 that 75% of students mentioned that this APL course is expected to be a good platform to prepare themselves for future employment or graduate research. Moreover, 88% of students are recommending APL to other students is another positive message to note.

Section-4: Experiments

In *Section-4: Experiments*, students had a chance to express their opinion about their favorite and challenging experiment during the course.

1. The most challenging experiment was (AFT/CEO/HALL/FUEL/FR/RUBY/SOL).

2. The easiest experiment for me was (AFT/CEO/HALL/FUEL/FR/RUBY/SOL).

Figure 4 depicts the results for the *Section-4: Experiments* statements. 50% of students found that HALL is the most challenging experiment. This could be affected by the fine motor skills required to solder fine wires. Although ugly soldering often led them to frustration, it generally did not affect the accuracy of their measurements, thus revealing an important lesson about the role of beauty versus function.

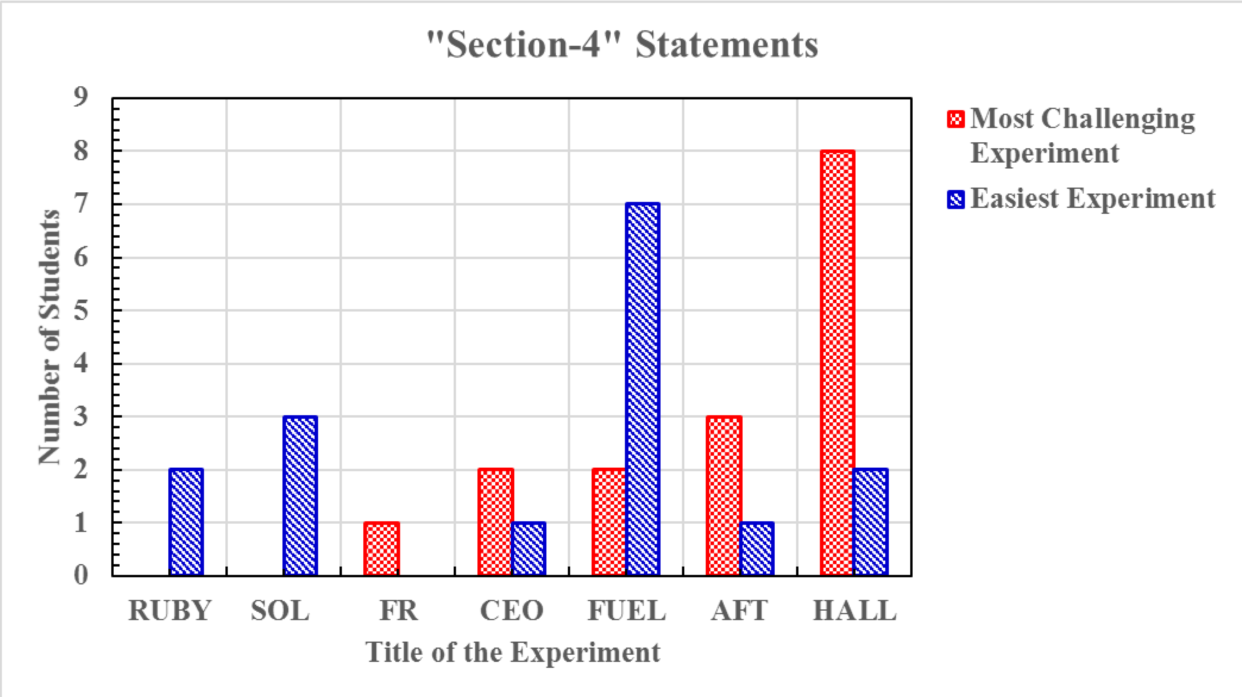

Figure 4: *Shows the survey results for the first two statements outlined in Section-4: Experiments.*

Also, 44% of students mentioned that FUEL was the easiest experiment. This is because of the pre-assembled kit purchased from the Pasco scientific with built-in silicon solar cell, electrolyzer and hydrogen fuel cell. Interestingly, none of them mentioned the FR as an easy experiment, indeed, it is one of the most sophisticated experiments in terms of optical bench arrangements, data collection and data analysis. The students noted that the AFT on acoustics was a favorite. Students were encouraged to bring in instruments to analyze, and even brought in a didgeridoo and bagpipes.

IV. Conclusions

In summary, a number of aspects are identified that are important for an advanced physics laboratory course. A course incorporating these aspects is aimed at providing students with tools that are crucial for future employment and advanced degree education. The frequent communication between students and instructors in the lab allows them to gain valuable experience with making pointed assessments and solving problems including troubleshooting. In addition, experience with a variety of apparatus was found to be useful. The written reports were not only graded, but were also edited in order to give them feedback before writing the following lab reports. The sequential editing and feedback on lab reports were essential for improving the students' written communications. At the end of course the survey gave us valuable feedback about the students' perception of the course, which we then used to modify experiments and procedures. Although it is difficult to quantify how the lab experiments were successful in preparing them for the future, we often get feedback from students that have returned from their three required 6-month Co-op experiences. Some students remarked that they used a particular apparatus for their Co-ops that they had used in the course, and some said that they needed to order apparatus at their workplace that they had used in the class. This feedback indicates the benefits of a large variety of experiments and apparatus.

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