Inquiry-Based Laboratory for Teaching Students Design-of-Experiments

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***Abstract*— Engineering professionals must have the ability to solve experimental open ended problems. Whether they work on physical problems directly or in a leadership role, they must be adept at the analysis and development of process solutions. The ability to address problems that have unknown or multiple possible solutions is essential for the success of new graduates, both in industry and in graduate school. Indeed, the ability to design experiments is a required technical outcome for ABET accredited engineering programs. This paper describes a laboratory course that includes a true inquiry based project. The use of a rubric facilitates teaching students to design an experiment and prepare to execute it. The design of experiments rubric was published previously and will be provided to the attendees, and is available online. A separate rubric that facilitates preparation of and grading of student lab reports is presented in this paper. The project is included as part of a Biochemical Engineering Laboratory Course at San Jose State University.**
Keywords—design of experiments, inquiry-based laboratory, biochemical engineering, rubric

I. Introduction

Engineering work requires students to perform experiments that have unknown outcomes. This is a level of learning that exceeds performing laboratory skills[1]. The US organization, ABET, has required of engineering programs seeking accreditation that they demonstrate how students are successful in design of experiments. The specific outcome is stated as "an ability to design and conduct experiments, as well as to analyze and interpret data".

While traditional cookbook experiments provide opportunities to students for learning laboratory techniques and the operation of equipment, they are ineffective at teaching students to design an experiment. Student-driven inquiry labs are becoming more common, but the logistics of enabling students free reign to implement a focused, unique experiment can seem to be burdensome for faculty. As a way to enrich the biochemical engineering laboratory curriculum at SJSU, students are assigned the task of designing an experiment of their choice during four of the 5-hour class periods. Students were given a rubric for the preparation of a short proposal of the experiment they had selected, and once the proposal was reviewed and accepted, they could then carry out their experiment. Experiments in the lab ranged in creativity from mere variations of the regularly assigned modules to altogether different procedures. The presentation will summarize the teaching and learning experience, logistics of lab organization, and a brief description of the rubric.

II. Methodology

A. CourseGoals

The overall goal of the course, which is taken by juniors, seniors and graduate students, is to teach the students the principle skills they need to contribute as engineers to the local biotechnology industries near or in Silicon Valley, California. Juniors who have taken the course have been able to successfully compete for internships during the summer at companies such as Genentech, BD Biosciences, Baxter, LS9, Boehringer Ingelheim, and various biotech start-ups. Through experience with skills in chromatography with a fast-performance liquid chromatograph, two weeks of protein methods including enzyme kinetics and cross flow ultrafiltration, bacterial fermentation and a two week module of molecular biology where the students perform a subcloning experiment, students are able to work in various aspects of process biotechnology. The four modules introduce the students to the basic skills and measurements, including analysis of total protein from a heterogeneous sample. The use of a detailed rubric for writing the lab reports also helps students to understand how to present and interpret results. The rubric is printed below in Figure I. Note that a score of 6 out of 10 is a C grade in the course, so the rubric is designed that the acceptable performance on each section is given 6 points.

10 pts. Define Goals and Objectives of the Experiment

0	No objectives identified
4	Objective identified but not relevant to experiment OR
	Contains technical or conceptual errors OR not measurable
6	Objective is conceptually correct and uses correct technical terminology but may be incomplete in scope.
8	Objective is complete, conceptually correct, concise, and uses correct technical terminology but may have grammatical errors.
10	Objective is complete, conceptually correct, concise, specific and clear, and uses correct technical terminology and grammar

30 pts. Present Experimental Results

I. Text

0	No text presented that explains the figures and tables
4	Some text is present that explains the figures and tables, but the text contains grossly erroneous statements.
6	Text is presented that describes all the tables and figures, but may be unclear, or contain grammatical or other minor errors.
8	Text is presented that completely and accurately describes the tables and figures but may contain grammatical errors
10	Text is presented that completely and accurately describes the tables and figures, and is grammatically correct.

II. Figures and Tables

0	Contains no relevant figures or tables
4	Contains figures and tables that are inaccurate representations of the experimental data
6	Contains figures and tables that are accurate but may be missing units or legends or captions such that not all the data can be understood by the reader
8	Containes figures and tables that are accurate and include legends, captions and units, but units may not be standard values as found in the literature.
10	All data is presented in meaningful way with appropriate units as shown in literature, and includes appropriate axis labels and captions.

III. Calculations (may be in an appendix)

0	Contains no relevant calculations in either results or appendix
4	Calculations are presented that are either missing some important data or have significant errors
6	All pertinent calculations are presented, but may contain some missing units or minor errors
8	All pertinent calculations are presented and are accurate, standard error calculation is shown but is either incomplete or inaccurate,
10	All pertinent calculations presented in results section are shown and are accurate, including calculation of the standard error

40 pts. Discuss Experimental Results

I. Interpret data in the results section

0	No interpretation of the data is included
4	Data is inaccurately interpreted
6	Some of the data is accurately interpreted but there are some minor mistakes in the interpretation
8	Most of the data is accurately interpreted without any mistakes in the interpretation or all of the data is interpreted but there are minor mistakes in interpretation or grammatical errors
10	All data and calculations found in the results section are accurately interpreted without grammatical error

B. Course Organization

Students must already have basic abilities in a wet lab course to succeed in the course. To identify students who have already mastered the necessary skills, on the first day of class students are tasked with measuring the extinction coefficient of a chemical that absorbs light in the visible range with a UV/Vis spectrophotometer, given a stock solution of known concentration (actual name of molecule omitted from the procedure). The ability to make dilutions and determine the standard error of their measurement is probed. Those students having significant difficulties with this are encouraged to take

II. Justify all the conclusions

0	The conclusions are not justified
4	Conclusions are inaccurately justified
6	Some of the conclusions are accurately justified but some are either not justified or inaccurately justified
8	Most of the conclusions are accurately justified but there may be minor inaccuracies or grammatical errors
10	All conclusions are clearly justified without grammatical errors

III. Explain the sources of error and/or equipment malfunctions

0	No explanation of any sources of error (if no standard error is calculated this section is necessarily a zero)
4	Justification of sources of error is inaccurate in a significant way or not all error is justified
6	Some of the error sources are accurately justified but some are ignored
8	Most of the error sources are accurately justified but there may be minor errors in the justification or grammatical errors
10	All presented error is justified including both systematic, human and random sources of error, and there are no grammatical errors

IV. Compare data obtained and any calculated values with literature

0	Experimental data is not compared to literature at all
4	Experimental data is compared in a significantly inaccurate way to literature
6	Some experimental data is compared to literature appropriately, but key data has not been compared or is inaccurate.
8	Key data is accurately compared to pertinent literature sources, including a direct (same units, same scale) comparison of major experimental findings but there may be grammatical or other minor errors.
10	Data is accurately compared to pertinent literature sources, including a direct (same units, same scale) comparison of major experimental findings and there are no grammatical errors.

20 Pts. Conclusions
Summarize the technical outcome of the experiment(s)

0	No conclusion is made
4	Inaccurate or irrelevant statements are listed in the conclusion section
6	Technical outcomes are stated but may lack precision, or contain minor inaccuracies, such as units or inappropriate/ vague statements.
8	All the technical outcomes are precisely stated, including presentation of appropriate error, but may contain minor errors that do not change the meaning of the concluding statements, such as grammatical errors
10	All the technical outcomes are precisely stated, including presentation of appropriate error, and without grammatical errors

Satisfy the question upon which the objective(s) are based

0	Statements are completely independent of the objective(s)
4	Experimental objectives are addressed in the conclusions but are inaccurately stated or compared.
6	Some experimental objectives are addressed in the conclusions, but not all, or statements contain minor interpretive errors
8	All the experimental objectives are addressed in the conclusions but either additional inappropriate information in also listed or the statements contain minor interpretive or grammatical errors.
10	All the objectives are completely and accurately addressed in the conclusions, are based on the experimental data and are grammatically correct.

FIG. 1. LAB REPORT RUBRIC

another lab class before registering for the Biochemical Engineering Lab class. After the first day the students who are accepted to take the course are placed in four groups. Students whose undergraduate programs include principally computer simulations and lack wet labs often need to take a lab class before they can take the Biochemical Engineering Laboratory course.

The following eight weeks of class are the four established modules that the students complete in their teams[2]. Because there is no time for lectures to help the student prepare for the lab experiments, a set of videos was prepared and posted on-line that show the instructor performing the skills. These videos are posted on youtube at the PackersClaire channel. These include how to run the FPLC, the fermentor, the steps of the molecular biology experiment[3], protein purification and general fermentation principles, and how to run other equipment in the lab. The videos were prepared with a simple camera and show the instructor running the experiments. Students are expected to watch the videos prior to beginning the relevant experiment, and to motivate them to prepare for their experiment a quiz is given at the beginning of the first period of the four modules.

The four modules are run by the students simultaneously for the eight weeks, which is challenging for the instructor. If the students prepare well, they can function relatively independently once they are shown where to find the materials they need, etc. The course is run in a semi-flipped[4] design with all the lectures and methods to be learned outside of the actual class period. This method has been run for the past 3 years. Most of the students find this strategy helpful, as they can even watch the videos during the class when they need to follow the various procedures.

The final five weeks are reserved for the student project. They are required to submit a simple proposal using a separate rubric for the design of experiments previously published[1]. At this point in the course the students are familiar with all the available equipment in the lab and with some encouragement and advising from the instructor have shown success in proposing another experiment that is different from those already run during the course. Some of the projects undertaken are listed in Table I.

TABLE I. SELECTED INQUIRY PROJECTS DEVELOPED BY STUDENTS IN CHE 194

1	Site directed muragenesis of Bl21-(DE3) pET-GFPuv E. coli (modification of start codon)
2	Evaluation of diafiltration for purification of milk protein
3	Production of E. coli Bl21 on glycerol
4	Stability of Vitamin C in natural orange juice during various sterilization methods
5	Effect of consumption of mono and di-saccharides on ethanol production by yeast
6	Expression of calmodulin in E. coli and purification with FPLC
7	Effect of pitching rates on diacetyl production in beer fermentation
8	Comparison of alpha acid production in home-brewed beer and commercial beers
9	Comparison of ethanol production in beer fermentation of lager yeast at three different temperatures
10	Optimization of polymerase chain reaction conditions in GFP subcloning experiment
11	Stability of trypsin following encapsulation in alginate beads: plug flow reactor evaluation

The above list is a selection of the projects designed by students in the course. The students developed their own experimental procedures and described in their proposals the methods for controlling the independent variables and measuring all the dependent variables.

Of note is the general enthusiasm for the projects. The students are willing to come to the lab even during the periods not dedicated to the course. The instructor is present for the purpose of safety and guidance, but the students have successfully managed their experiments independent of the instructor assistance. The final class period is dedicated to student presentations.

III. Discussion

The lab report rubric serves the function of both instructing the students in proper lab report writing and facilitates grading the reports both fairly and quickly. The use of the rubric helps the students to understand exactly what is expected of them with regard to the report, and dramatically reduces the grading time. As a way to motivate the students, the lowest grade of the four reports is dropped from the final grade of the course, so they have a chance to try to write the report well and learn from their first attempt how to get it right.

The course provides a great experience for the students to learn how to solve a problem that does not have a known solution. Some instructors may be uncomfortable working with the students on an experiment for which they are also unfamiliar, but this is precisely when the students flourish. When they have the opportunity to take ownership of their project, it seems to cause them to try harder to find the solution. The approach is similar to working with students doing research.

The first two years this course was run with the inquiry portion, only 2 weeks were allotted for the project. The result was generally failed experiments without the opportunity to repeat the tests. For the past three years, five weeks have been dedicated to this project. The result of the longer time frame has been remarkable in terms of student success. Now the students are able to test the methods during the first two periods and then perform the actual experiment during the last weeks, or repeat the procedure with knowledge of the critical steps.

It may seem that it is not feasible to offer this opportunity in a resource-poor institution, however, the strategy is to show the students which pieces of equipment they have access to and allow them to find a problem that they have the resources to answer. It is easier now to find equipment for labs from companies that change out their instruments or have to close for financial reasons. Indeed, some of the experiments that were done by the students did not require expensive equipment at all.

Design of the experiment requires a higher level of thinking than simply following the steps that are described in an instruction manual. In addition, the evaluation of the outcome normally cannot be found online or from students who took the course previously. Students thus learn how to present their results and articulate the interpretation of the outcomes in a report and presentation, which are very helpful skills in their seeking employment.

IV. Conclusion

A biochemical engineering laboratory course has included a project that involves student design of experiment. This has been run for five years with the key elements of success being to allow the students sufficient time (five weeks of lab) to test the principle methods and repeat steps knowing the critical steps to success. This experience has been valuable for the students to be able to compete for internships at San Francisco Bay Area biotechnology companies.

References

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