Design of Experiments:
Student Response to an Experiential Learning Approach

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Abstract

ABET Student Outcome b) calls for engineering programs to demonstrate that students have "an ability to design and conduct experiments, as well as to analyze and interpret data"[1]. Our department, as likely have many others across the country, has historically addressed this curriculum requirement with instruction in statistics and uncertainty analysis either in lab or other courses. Does presenting the fundamentals of statistical analysis, uncertainty and error propagation truly give students the ability to design experiments? What, exactly, are program evaluators looking for as evidence that the students in a program are demonstrating the ability to "design and conduct experiments"?

In this paper, an experiential approach to ensuring that students have some training in design of experiments is described along with the responses to a student survey assessing their attitudes toward this approach and how they perceived its effect on their laboratory learning experience.

Background

A cursory review of the topic of experiment design will inevitably lead one to who many consider the "father" of the topic, Sir R.A. Fisher who, in 1935, published likely the first text on the subject Design of Experiments[2]. By the 1960's, several books on design of experiments in a number of areas of study had been published with two of the most commonly used such texts in engineering programs being Engineering Experimentation by Tuve and Dumholdt[3] and Experimental Methods for Engineers by Holman[4]. However, the subject of design of experiments was generally not present, or confined to a discussion of the mathematics of statistics and uncertainty in these texts until editions published much closer to the present time. For further discussion of the history and development of experiment design topics in popular texts, see Appendix 2.

Innovation in laboratory courses and equipment has been consistently present, but typically at a low incidence, in general engineering education conferences. As an example, an analysis of the last nine ASEE Midwest Conference Proceedings[5] yielded a total of 35 papers directly related to engineering laboratory courses with another three to four papers devoted to related topics. This number comprised just over 10% of the 337 total papers presented at these meetings. Of the 38 papers directly or closely related to lab courses, the topical area of each could be classified as equipment use/development (24), student learning/participation enhancement (9), or teamwork (2). This classification leaves only three papers related to the general area of design of experiments. Of these three, two address the more traditional topic of statistical/sampling design with only one paper with a similar focus to the topic at hand.

This last paper, “Incorporating Inquiry-Based Projects into the Early Lab Experience” by Servoss and Clausen[6] was presented at the 2012 ASEE Midwest Conference held at Missouri University of Science and Technology describes a methodology with several similarities to the one independently developed by the current author and used in a sophomore level Chemical Engineering lab course to address student attention and interest in the course.

As further background to the method described here, a short history of the various approaches used within our department is in order. Mechanical Lab II is a required course in the ME program at Arkansas Tech University and is typically taken during the senior year, often during the last semester of a student’s curriculum. The course currently contains experiments in fluids and has the senior level course in Fluid Mechanics as its primary pre-requisite. Mechanical Lab II was one of the first courses the author was assigned upon joining the faculty 20-some years ago and he has continued to teach it, although not consistently every year, since that time. In initial offerings of the course, the author followed the traditional methodology that he had been exposed to as an undergraduate: a fairly well prescribed experiment with clearly stated goals and procedures that the students were expected to follow, and regurgitate, in the report. Reports were expected to be, more or less, formal laboratory write-ups with a summary, introduction, procedures & set-up, results, and conclusions sections.

This arrangement was continued for many years until shortly after the conversion to outcomes based ABET assessment and the establishment of the student outcomes. As many others likely did, the department struggled with defining performance criteria and assessment methods for many of the “soft skills” outcomes, but, among the more technically based outcomes, outcome b) always caused the most consternation. Initially, the department chose to put more emphasis on the second part of the outcome “to analyze and interpret data” and only superficially addressed the “design” part of “design and conduct experiments”. The rationale was that data analysis and reduction was an integral part of experiment design, through determining what data was needed, how many trials or measurements were needed, and, thus, the requirement for design was being met.

As new faculty rotated into the course, different points were emphasized in its presentation and grading. Some continued to put emphasis on data reduction and uncertainty analysis, others on report writing, and others on comparison of experimental data to modeling calculations. Neither this course, nor the requirements under student outcome b) have ever been cited by any of the ABET PEVs that visited campus during this time as a problem area. However, the questions at the department level regarding the course and outcome b) remained.

Implementing the Experiential Approach

When the author was assigned both sections of the lab for the Spring, 2013 semester, he referred back to an approach he had used in a special “mini-session” offering several summers previously. At that time, the department was testing a new means of course offering in which some lab courses were taught in a condensed, three-week long session held between the end of spring and the first summer session. Due to the quick turnaround required during this mini-session, all reports were done as team reports and each team had been assigned one of the pre-lab briefings in order to increase their participation level. This previous methodology was refined and expanded into that used during this past spring semester. The methodology can best be described by the following process:

1. The students in the class (normally 10 to 12 per section) are divided into three (3) teams which remain together throughout the semester

2. The first two weeks of the semester are devoted to discussions of report writing, data reduction and analysis, and uncertainty calculations.

3. The initial lab is "instructor presented" in the traditional manner and students are required to submit individual reports

4. For the next three lab experiments, the groups take turns as the "lead" group for the instructor specified experiments.

5. The lead group is responsible for preparing the pre-lab lecture/briefing, determining the type and number of data to be taken, and serving as the "instructor" during the experiment.

6. Students not on the lead team for a given experiment submit individual reports while the lead team submits a team report with an "Observations" section replacing the "Results".

7. After mid-term, a second round of "student designed" labs is completed during which the lead team for each lab is responsible for specifying the experiment to be performed including all details. The course instructor acts only as an advisor for these labs.

The intention of this methodology is to move the students from participating in the experiments purely at a "technician" level; following provided procedures, taking specified number and type of data, to a more involved "engineer" level in which they participate in the experiment planning, study the background theory, and have input into the conduct of the experiment. When carried out in this manner, there would seem to be little question that this lab course was giving students "the ability to design and conduct experiments". In order to successfully achieve the goals of the final round of experiments, students will have to consider what data needs to be taken to measure the desired quantity or phenomenon, consider equipment needs including constraints due to what is available, consider what procedures need to be carried out, and consider how to ensure that enough data points are taken to produce a useful result. Thus, the methodology presented should meet all of the desired student outcomes of a senior level engineering lab.

Student Response

The above methodology was used during the conduct of two sections of Mechanical Lab II at Arkansas Tech University during the spring semester of 2013. Each section of the lab had an enrollment of 10 students which resulted in two teams of three and one team of four in each section. Each section met one afternoon per week during the semester and each section conducted the same four experiments for the instructor-led experiment and the first round of student-led experiments. During the round of “student designed” labs, there were two common experiments and one that differed between the two sections. Each section was given a final exam during their last class period and following this exam a survey was administered to attempt to gain understanding into the student’s attitudes and opinions of the methodology used for the class. Students were instructed not to provide identification on the survey, told that the survey results may be used in this paper and told that the instructor would not access the surveys until after submission of final grades for the course. The full results from this survey administration are provided in Appendix 1 and are discussed in summary below. Note that on the actual survey some questions used a low-to-high (least to most favorable) rating scale while other questions used a high-to-low scale. All results discussed below have been converted to low-to-high scales for ease of discussion and comparison.

Survey Results

The survey consisted of 18 questions divided into three topics with responses for each rated on a three to five-point scale. The initial set of six questions asked the students to rate their level of learning on topics contained within the course. The next set of four questions asked students to rate the usefulness of the student-led pre-labs. And the final set of eight questions asked them to consider the effectiveness of student-led labs versus the traditional instructor-led methodology. All 20 students enrolled in the two sections completed the survey. Responses were not separated by section as there was no discernible difference between the sections. Table 1 below summarizes the student responses and a more detailed explanation of the response to each question follows.

Table 1. Student survey response summary.

Assessment	Question/Topic	Response Scale	Average Response
Level of Learning	Fluid mechanics	1-4	3.1
	Data processing, uncertainty	1-4	2.65
	Report writing	1-4	3.15
	Lab experiment planning	1-4	3.4
	Lab experiment design	1-4	3.35
	Record keeping	1-4	3.05
Usefulness of Student-led pre-labs	Preparation for conducting the lab	1-4	3.2
	Understanding the purpose/goal of the lab	1-4	3.1
	Understanding the theory behind the lab	1-4	3.0
	Information needed to write the report	1-4	2.95
Effectiveness of student-led vs. instructor-led labs	Labs in which you were on the lead team – learning level	1-4	3.1
	Labs led by another team – learning level	1-4	1.85

	Labs in which you were on the lead team – prep for report writing	1-3	2.6
	Labs led by another team – report prep	1-3	1.58
Overall impressions	Methodology used in lab	1-5	4.15
	Progression of responsibility	1-5	4.1
	Contribution of student-led labs to learning	1-5	3.6
	Contribution of student-lad labs to grade	1-5	3.4

For the first section, the average response on the four point scale (1- low, 4 – high) ranged from a low of 2.65 to a high of 3.4. The lowest rated response was related to the student's level of learning of data processing and uncertainty analysis while the highest rated response was related to level of learning of lab experiment planning with lab experiment design coming in a close second (3.35). This data is admittedly very preliminary and has no control to compare to, but it seems apparent that the students at least recognized that the course was attempting to instruct them in experiment design and planning. (Note that this fact was not stressed during the course and may not have been mentioned explicitly at any time.) Overall, the average response of the students on this topic area, level of learning in the course, averaged 3.12 out of four.

For the second section of the survey, which asked for the students' perception of the usefulness of the student-led pre-lab briefings, the average response on the four point scale ranged from a low of 2.95 to a high of 3.2. The lowest rated response was related to information provided that was needed to write the report, while the highest rated response was related to preparation for conducting the lab. Overall responses for this section averaged 3.06. As can be seen from the high and low response averages, there was little spread in the responses on this section and the responses were generally, but not overwhelmingly, positive.

In the final section of the survey, students were asked to compare the effectiveness of student-led versus instructor-led labs. The rating scales in this section ranged from three to five points. The first two questions asked students to assess their level of learning in those labs in which they were on the lead team and in those in which another student group was the lead team. Probably predictably, the students rated their learning level high (average of 3.1 out of 4) for the labs in which they were on the lead team but an appreciably lower rating (1.85 of 4) for the labs led by another student team. Similarly, the responses to the next two questions, asking for an assessment of their level of readiness to write a good lab report, produced a much higher rating (2.6 on a 3 point scale) for labs in which they were on the lead team than those led by another student group (1.58 of 3).

The final four questions, all of which used a five point rating scale, asked the students' impressions/opinions on the format (methodology) and its progression used in the course and the contribution of the student-led labs to their learning and to their grade in the course. For these four questions, there was a noticeable but smaller difference in the responses. Questions 15 and 16, which asked the students' impression of the methodology and the progression used (instructor-led then student-led then student designed labs) resulted in ratings of 4.15 and 4.1, respectively, on the five point scale. Conversely, the last two questions, asking the students' opinions of how the student-led labs contributed to their learning and to their grades in the course resulted in ratings of 3.6 and 3.4, respectively.

From these results, one can conclude that the students had an overall positive reaction to the inclusion of student-led and student-designed labs into the lab course. Particularly pleasing is the response to questions 4 and 5 in which the students gave high ratings to their level of learning regarding experiment design and planning. There was, however, a rather distinct difference in rating learning in those labs in which the student was on the lead team, versus those labs in which another student team was the lead group. While this is to be expected, the level of variance was higher than would be hoped for.

Instructor's Impressions

From the point of view of the instructor of the course, the evaluation of the effectiveness of the student-led labs was a bit different from that of the students. There were several positive occurrences that, it would seem, can be attributed to the use of student-led/designed labs. Primary among these is the higher level of participation in lab preparation for the lead teams. The number of office visits and questions about the upcoming experiment was much higher than in previous experiences which did not include student-led labs. The level of accuracy and competence in the Theory section of the lead team reports was, generally, higher than that of the other students. Finally, as evidenced from the survey results and anecdotal evidence from student comments, the use of student-led labs seems to have raised the level of at least awareness regarding the purpose and conduct of engineering experiments.

Along with these positives came, of course, some negatives. The primary negative, from the instructor's point of view, of the student-led labs was the almost universally poor quality of the pre-lab briefings. Typically, these consisted of the lead team writing the primary equations that would be needed in reducing the labs' data on the board, announcing what equipment was to be used, what measurements were to be taken, and then something along the line of "and you will use these equations to calculate 'X'". Very little in the way of theory behind the phenomenon was discussed and often intermediate calculations or other considerations were omitted or glossed over. While the students gave the overall usefulness of the student delivered pre-lab lectures a 3.06 rating on a four point scale, virtually any independent evaluator would rate them much lower.

The other chief problem encountered throughout the semester was the students struggle in crafting acceptable lab reports. The sections containing background theory were, almost universally, over simplified, if not outright wrong, and the "discussion" of results often consisted of a series of data tables with simple introductory sentences at best. These difficulties in report writing, however, were likely not a result of the methodology used for the course, but would have very likely been encountered in any case.

Recognizing that the results presented here are preliminary, at best, the results are promising enough to encourage the future use of this methodology. Some changes that could be made to address the primary weakness identified could include assigning a grade to the pre-lab presentations separate from the lead team report grade, having required meeting times with each team one or two days prior to their presentation, or requiring pre-approval of a presentation outline. Along with any or all of these changes, it appears obvious that there is a need for a greater level of involvement and instruction on experiment design and preparation with the teams leading up to the week/day of their experiment. While the main purpose of this methodology is for the students to experience experiment planning and design, the laboratory instructional needs of the other students cannot be compromised to the extent it was during this past course offering.

In addition, the student designed labs could be taken a step further in order to try to simulate in the problem assignment a task that might be more representative of a real world experience. An initial idea along this vein is to describe a phenomenon that is affecting a product and ask the team to devise an experiment to measure some quantity associated with this phenomenon to help address the problem. As an example, customers have been complaining about an oil that our company produces breaking down at slightly elevated temperatures. An experiment that could help address this would be to measure the oil's viscosity at a variety of temperatures including the range in which problems were reported.

Conclusion

From both the results of the student survey and personal observations it seems evident that there is some promise in the use of student-led and student-designed labs in an upper-level lab course leading to better preparation for experiment design and conduct. Some problems were encountered that were related to this inclusion while other problems likely would be present with or without the use of student-led labs. Further refinement and assessment of this approach would be necessary in order to both address those problems encountered and to fully evaluate the effectiveness of this methodology.

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Appendix 1

Course Survey

Since I forgot to request course evaluation forms for this semester, I wanted to give you the chance to have some feedback on the course. Also, I may use some of this info as part of a paper I'm considering submitting regarding my methodology for running this course.
Please complete the following survey honestly. I will not have access to these responses until after grades have been posted. Do not put your name on these pages.

Please rate the level of learning in each of the following topic areas that you feel you achieved in completing Mechanical Lab II this semester:

Fluid mechanics:
___I learned nothing 2_ I learned a few things _14_ I learned several things _4_ I learned a lot

Data processing, uncertainty:
_1_I learned nothing _6_ I learned a few things _12_ I learned several things _1_ I learned a lot

Report writing:
1_I learned nothing _4_ I learned a few things _10_ I learned several things _6_ I learned a lot

Lab experiment planning:
__I learned nothing _3_ I learned a few things _6_ I learned several things _11_ I learned a lot

Lab experiment design:
__I learned nothing _2_ I learned a few things _9_ I learned several things _9_ I learned a lot

Record keeping:
__I learned nothing _5_ I learned a few things _9_ I learned several things _6_ I learned a lot

In the next few questions, please rate the usefulness of the student-led and delivered pre-lab lectures that introduced labs #2-7.

Preparation for conducting the lab:
____Practically useless ___ Barely sufficient _16_ Adequate _4_ Very effective

Understanding the purpose/goal of the lab:
____Practically useless _4_ Barely sufficient _10_ Adequate _6_ Very effective

Understanding the theory behind the lab/phenomenon:
____Practically useless _7_ Barely sufficient _6_ Adequate _7_ Very effective

Information needed to write the report:
____Practically useless _3_ Barely sufficient _15_ Adequate _2_ Very effective

In the following questions, consider the effectiveness of having student-led labs versus the traditional 100% instructor led labs.

For those labs in which your team was the lead team, compared to an instructor led lab did you feel that you:
_5_ learned much more _12_ learned some more _3_ learned about the same ___ learned less

For those labs led by another student team, compare to an instructor led lab did you feel that you:
_2_ learned much more _2_ learned some more _7_ learned about the same _9_ learned less

Thinking about how the pre-lab lecture prepared you to write a good lab report, for those labs in which your team was the lead team, compared to an instructor led lab did you feel that you:
_14_ were better prepared _4_ made no difference _2_ were less prepared

Thinking about how the pre-lab lecture prepared you to write a good lab report, for those labs which were led by another student team, compared to an instructor led lab did you feel that you:
_2_ were better prepared _7_ made no difference _10_ were less prepared *(one left blank)*

Overall, what was your impression of the format used in this lab course this semester:
___ very unfavorable ___ unfavorable _2_ neutral _13_ favorable _5_ very favorable

Overall, what was your impression of the progression of the labs (i.e. in initial instructor led lab, followed by instructor-selected/student-led labs, followed by student-selected/student-led labs)
___ very unfavorable ___ unfavorable _5_ neutral _8_ favorable _7_ very favorable

In your opinion, did the use of student led labs contribute positively or negatively toward your learning in the course?
___ very positively _12_ positively _8_ no effect ___ negatively ___ very negatively.

In your opinion, did the use of student led labs contribute positively or negatively toward your grade in the course?
___ very positively _8_ positively _12_ no effect ___ negatively ___ very negatively.

Thank you very much for your time and thoughts. If you have any further thoughts/comments/etc. that you would like to pass along, feel free to use the back of this sheet.

Appendix 2

Additional History of Experiment Design in Texts

Although scientific inquiry and the use of experiments dates back hundreds, thousands of years in mankind's history, a search for information on "design of experiments" inevitably leads one to what is widely considered the seminal text on the topic by Sir R. A. Fisher published in 1935[1]. In his preface, Fisher describes the purpose of the book as showing the power of using statistical analysis in, not only the analysis of results, but the design of experiments. This text was continually updated and revised by Fisher through seven editions with an additional two editions, containing primarily corrections and minor changes, published after his death in Australia in 1962. Fisher was trained as a mathematician, and he first began to develop his ideas in the early 1920's while working as a statistician at Rothamsted Experiment Station in Harpenden, England[2]. Fisher introduced many of the methods now accepted as standard in experimental investigations such as randomization of trials, Latin square and factorial block patterns, and confounding.

Since Fisher's initial text, many additional books have been published under the topic of experimental design. The majority of these, however, did not come along until several years after Fisher's 1935 publication. In the preface to a 1973 reprint of his text, "Design and Analysis of Experiments", Oscar Kempthorne notes that at the time he wrote his first edition, 1948-1950, "there were only two books devoted to the topic"[3]. Those being Fisher's and "Experimental Designs", by W.G. Cochran and G.M. Cox. Kempthorne's original preface pays further homage to Fisher, and his colleague F. Yates, for being largely responsible for the building of the topic of experimental design. Kempthorne's book contains most of the common topics in data analysis including basic statistics, least squares theory, and multiple regression, along with experiment design techniques including randomized blocks, Latin squares, confounding, higher order factorial designs, and so forth.

Since Fisher's main area of experimentation was in field trials of various agricultural treatments, much of his writing is devoted to the application of his methods to such trials. This influence carries through in Kempthorne's text with chapters devoted to plot techniques and lattice designs. With maturation of the topic came an expansion into many other scientific areas with associated specialized texts. As an illustration, a search for books using the title keywords "design of experiments" at the Arkansas Tech library resulted in 16 results with areas represented ranging from behavioral research and education to ecology and engineering. The vast majority of the early publications were written by statisticians, but most of the texts devoted to specific areas of inquiry have been written by those trained in that field of science. One of the many publications specifically devoted to engineering experiments that were published in this period is the 1973 publication, "Statistical Design and Analysis of Engineering Experiments," by C. Lipson and N. Sheth[4], a professor of mechanical engineering and a Ford research engineer respectively. This book contains the standard chapters on statistics and correlation, regression and variation analysis, but the chapters on plot design are absent with more typical engineering topics represented such as product quality and uniformity, fatigue and analysis of systems.

One of the classic texts used for college engineering laboratory classes was also initially published in this same time frame. J.P. Holman's "Experimental Methods for Engineers" first appeared in 1966. Holman's text contained less material on the strict statistics-based design of experiments and, instead, focused more on the typical type of measurements made and equipment used by engineers. The second edition, published in 1971 features a single chapter on data analysis with the remainder of the chapters devoted to specific areas of experiments and measurements (e.g. "Motion and Vibration Measurement" and "The Measurement of Temperature")[5]. This theme was repeated in other popular lab texts such as "Engineering Experimentation", by G.L. Tuve and L.C. Dumholdt which addressed laboratory/experiment project planning and design and data analysis in two short, introductory chapters with the remainder of the book devoted to describing various types of measurements and the equipment used to make them[6]. Many (almost all?) of today's senior engineering faculty were trained with such texts and while the topic of experimental design was a mature subject with a variety of explanatory texts available, the emphasis in many programs, certainly that of the author, was on the proper use of instruments and presentation of data/results.

As engineering education moved into the 21st century, the emphasis in program accreditation changed from one of counting assets to one of measuring program outcomes (i.e. student abilities). Along with this change came changes in textbooks. By the 2001 publication date of the 7th edition[7], Holman's text had grown to include chapters on experiment design and report writing. At the same time, the chapter on analysis of data expanded. Thus, it seems that popular textbook authors have recognized the need for training in experiment design, the question remains as to whether engineering programs have also changed their methods to address this need.

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