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Student Designed Lab Experiments: How Students Use Pedagogical Best Practices

Dr. Bridget M. Smyser, Northeastern University

Dr. Smyser is an Assistant Academic Specialist and the Lab Director of the Mechanical and Industrial Engineering.

Dr. Gregory J Kowalski, Northeastern University
Andrew F. Carbonar, Northeastern University

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Abstract

The pedagogy of laboratory courses has been well discussed in the literature, but the extent to which these best practices are incorporated into laboratory experiment design varies wildly. At Northeastern University, various capstone design teams over the years have been tasked with designing new experimental apparatus for the undergraduate teaching laboratories along with appropriate lab handouts and other instructional material. In many cases, the students involved in these projects have taken the lab class for which they are designing the experiment and have reported negative experiences, and therefore are motivated to try to improve the class for future students. Student designed labs have the potential to reduce burden on instructors. Student developers may also provide a unique viewpoint that could result in labs that are more engaging for the student body. Historically, some of these student designed experiments have been incorporated into lab classes successfully, and some have not. Currently, there are three separate capstone teams involved in developing new experiments for the Internal Combustion Engines course and the Dynamics and Vibrations course. Past and current capstone projects were examined to determine the extent to which student designed labs incorporated established pedagogical best practices into their designs. Common features of successful and unsuccessful designs were also examined. Initial results indicate that one of the key features was a strong collaboration with an individual lab instructor, as even the best experimental apparatus will not be used if an instructor does not see the value of incorporating it into their course. It also seems that teams who incorporate pedagogical research produce more sophisticated apparatus from a design perspective. Finally, reflections of the students involved in the development of these experiments are examined in order to gain insight into how students perceive and use pedagogical information in their designs.

Introduction

It has been established by a number of authors that laboratory experiments and experimental apparatus can be effectively designed by undergraduate students. There are a number of reasons to use undergraduate students to create lab experiments. Commercially available lab equipment is often expensive and space intensive. Technician support is often limited, so the ability of technicians to develop new equipment becomes limited as well. In some cases, the commercially available equipment does align with the desired course outcomes. Worse, some commercial equipment lends itself to cookbook type experiments that require limited student interaction, or have little flexibility. When space is severely limited, mobile experimental stations can provide lab experiences in the classroom or any other available space, however these are not often commercially available.

Universities have used various approaches to allow students to develop their own experiments and/or lab equipment. There are many cases in the literature of students designing their own experiments with available experimental apparatus.[1,2,3] Although this experience in "ability to design and conduct experiments" is critical for engineers and is one of the ABET criteria[4], this is not the same as creating an entirely new experiment with newly designed equipment. In one case a special topics course was developed to allow students to develop labs for a new course.[5] This experience gave student groups complete responsibility for developing a new laboratory, including experiments and teaching materials. Although this had the benefit of reducing the startup time for the new laboratory, it was a one-time experience, not an ongoing concern. Other universities have also had students develop their own experiments as senior design projects, or as a smaller part of a traditional lab report.[6,7] What is unclear is how long these experiments endured after the class or project, and how completely they were incorporated into the lab course for which they were designed.

In a paper by Peuker, a unique approach to student designed equipment for teaching laboratories[8] is described. It is also noted that the expense and inflexibility of commercial lab equipment can make it unattractive to some universities. In Peuker's program, industry partners donated some equipment, and student capstone teams partnered with local industry to develop the experiments. Despite the benefits of industry partners, there were some limitations to the approach. The resulting projects tended to be demonstrations, or somewhat limited in what the students could control. It did not appear that pedagogical literature was consulted, or that pedagogy was considered as a major part of the design. One interesting point was the author's belief that it was the industry partnerships that really made the projects successful.

When labs are designed by students, the design requirements vary widely. Beyond the physical specifications that the labs must satisfy, there is often the requirement that the students create lab handouts, questions, or other materials to accompany the apparatus. What is not clear, however, is how much the students who create these experiments tap into the literature on the pedagogy of laboratory experiments. Kolb's experiential learning cycle[9], the ABET requirements[4], and other schemes outline best practices for developing lab experiments. The best labs are those which allow students control over the experiments, provide the opportunity to learn from mistakes, allow students to collect and use their own data, and provide students the opportunity to learn to design experiments. Looking at previous works, it is often unclear whether or not the students availed themselves of the pedagogical literature in the process of developing their design.

The specific questions this current research aims to answer are:

- What are the characteristics of successful lab design projects?
- How do students use pedagogical literature to design educational lab equipment?
- Does the use of pedagogical concepts improve the resultant lab designs?
- What determines whether or not student designed equipment is adopted by a department or course?

Capstone Projects in Experimental Design

The capstone design sequence in the Mechanical and Industrial Engineering department at Northeastern University is a two semester required course for senior students. Students work in teams of 3-5 members with the goal to produce a working prototype at the end. Projects can be industrially sponsored, student proposed, or faculty sponsored. The faculty sponsored projects vary widely, and can include designing equipment for research labs, working on commercial product ideas, or designing equipment for undergraduate teaching labs. This investigation is restricted to projects related to teaching laboratories. Capstone teams are particularly valuable for developing equipment for labs that are small, for elective courses, and for courses that need a hands on component without having a physical lab space. Since 1995 there have been 14 different project teams that have been tasked with designing equipment and experiments for the teaching laboratories, including 3 projects that are currently underway. These projects, listed in Table 1 below, have varied from industrial engineering projects with minimal physical apparatus needed to internal combustion engine laboratories which required multiple groups developing and refining numerous pieces of equipment over a number of years. Unlike some other schools, none of these lab design projects typically involved a formal partnership with industry, although occasionally the efforts of the students procured donations from certain companies.

Table 1: Experimental design projects in capstone design course

Year	Project Name
1995-96	Design and Construction of a Gear Exhibit
1996-97	Construction of a Laboratory to Study Gas Flow Concepts
1996-97	Design and Construction of a Laboratory Facility to Demonstrate Engine Control
1997-98	Continuation of the Development of a Laboratory for the Internal Combustion Engine Course
1998-99	Design of a Laboratory Setup to Measure Air Mass Flow Rate
1998-99	Design of a Laboratory Setup for the Measurement of an Air Motor Efficiency
2005-06	Transforming Industrial Engineering Theory into a Companion Laboratory with Practical Applications
2007-08	Classroom Laboratory Flexible Manufacturing System
2011-12	Design of Set up for Flow Visualization
2012-13	Kinematic Demonstration Models Designed to be Universally 3D Printed
2013-14	Internal Combustion Engine Laboratory
2014-15	Internal Combustion Engine Laboratory II
2014-15	Development of Human Factors Lab
2014-15	Design of New Dynamics and Vibrations Experiments

These projects were examined in order to determine whether or not they had included pedagogical literature in their design and if they were incorporated into the class for which they were built. They were also scored using a scoring rubric previously published by the authors[10]. This score judged both the completeness of the prototype at a point 3 weeks before the end of term, and also whether the students had tested or validated their design at that point. At a point three weeks prior to the end of the course, teams must produce an Executive Summary that is sent out to the alumni jury that judges the final presentations. It is understood that the projects are not necessarily going to be completed at this point. Therefore, assessing the prototypes for completeness and extent of testing completed at this point has been found to be a good predictor of team effectiveness. The prototypes are assigned a score of 1-5 for completeness, where 5 indicates a completed prototype and 1 indicates that no prototype is likely by the end of the course. Testing was also rated on a 1-5 scale, where 5 indicates that prototype verification testing is complete and 1 indicates that testing was not planned or discussed. This validated rubric is presented in Table 2. In addition to scoring the executive summary, grades are determined based on oral and written reports and whether the final projects met the specifications laid out by the team and their advisor at the beginning of the course. For the design of lab equipment and experiments, the prototype was considered complete not only if the physical apparatus was finished, but also if the lab handouts and other documentation was complete.

Table 2: Capstone Executive Summary Scoring Rubric, also called the Prototype Score.

Solution Score	Testing/Validation score
5 = Fully developed solution	**5** = Fully tested and validated
4 = Solution partially developed	**4** = Testing substantially done
3 = In progress, solution expected by course end	**3** = Testing planned and in progress
2 = Solution in progress, unlikely to meet all specifications by end of course	**2** = Testing planned, unlikely to be complete by end of course or not started
1 = Working solution unlikely by course end	**1** = Testing not discussed or planned

Analysis of Past Projects

Table 3 below shows the past experimental design projects along with their prototype scores. Projects that are currently in progress were excluded from this analysis. In addition, the final reports and executive summaries were read closely to determine if the pedagogical literature had been consulted as a part of the design process. Advisors and professors who have been in the department for a long time, were consulted in order to determine whether the various experiments had ever been adopted by a laboratory class. Some experimental equipment is still present in various labs as well. It should be noted that the use of the pedagogical literature was not required since part of the assessment process involves the students' ability to conduct a relevant literature review.

Table 3: Project scores and analysis

Project Number	Project Name	Prototype Score	Consulted pedagogical literature?	Adopted by class?
1	Design and Construction of a Gear Exhibit	5	No	Used once as demo
2	Construction of a Laboratory to Study Gas Flow Concepts	4	No	No
3	Design and Construction of a Laboratory Facility to Demonstrate Engine Control	5	No	Yes
4	Continuation of the Development of a Laboratory for the Internal Combustion Engine Course	10	No	Yes
5	Design of a Laboratory Setup to Measure Air Mass Flow Rate	4	No	No
6	Design of a Laboratory Setup for the Measurement of an Air Motor Efficiency	6	No	No
7	Transforming Industrial Engineering Theory into a Companion Laboratory with Practical Applications	10	Yes	Yes
8	Classroom Laboratory Flexible Manufacturing System	4	No	No
9	Design of Set up for Flow Visualization	10	No	No
10	Kinematic Demonstration Models Designed to be Universally 3D Printed	10	Yes	Yes
11	Internal Combustion Engine Laboratory	5	Yes	Yes

Projects tend to fall into a number of categories. Certain courses in the curriculum did not initially have a lab component connected to them. Projects 3,4,7,8, and 11 in Table 3 fall into this category. The Internal Combustion Engine course originally had no hands on components. The professor who teaches this course also advises capstone design teams, and thus was in a unique position to champion a series of projects that would directly benefit his course. This course had very little physical space that could be dedicated to lab equipment. This is also an elective course, with a maximum of 30 students per offering, which means that there was not a lot of institutional support to dedicate a large amount of space and money to a course that served such a small number of students. Commercially available equipment for internal combustion engine studies tends to be extremely large and expensive. Because of all these factors, the initial two projects that constructed equipment for this lab were highly desired, and were adopted for a long time. The most recent projects that are working on equipment for this lab were also championed by the same professor. The original equipment had lasted long enough to become outdated, which speaks to the robustness of the initial design. However, the more recent projects have really embraced pedagogical concepts. The newest experiments deliberately incorporated “team-based learning, objective data analysis, and theoretical vs. experimental results comparison” based on their research into the state of the art of laboratory development pedagogies[11].

Project 7 above similarly used laboratory development pedagogies to develop a hands on lab experience for industrial engineering students. The instructor of this course also recognized the benefits of hands on experience in industrial engineering concepts such as material handling, work design, quality control, and queuing. However, this course had absolutely no lab space available, so the experimental equipment had to be stored in a closet and easily brought out for the activity. The students working on this project developed a Lego car project that could be broken down into sub-assemblies and used to get data for analysis. This project was strongly supported by the course instructor, and is still being used 10 years later. However, another industrial engineering lab project, Project 8, was not particularly successful either as a design or in being adopted by a class. This was a rather ambitious attempt to design a flexible manufacturing system that could be rolled into a classroom and then stored when not in use. The team combined ME and IE students, to incorporate both IE concepts and allow for the mechanical knowhow to build the equipment. It became clear early on that this would need to be a multi-phase project, and that doing it inexpensively with student-constructed equipment was not going to be possible. Group issues between the two majors, and a lack of a strong course based faculty champion, meant that no prototype was ultimately constructed, and the idea was abandoned with no further phases.

None of the projects with prototype scores less than 5 had consulted the pedagogical literature. These projects (Projects 2, 5, and 8 in Table 2) tended to be designed around concepts, rather than particular classes. Project 2 intended to study gas flow concepts. Although the group recognized various concepts as being essential for ME students to know about, the project was not designed with a particular class in mind. Thus the equipment did ultimately work, but then sat around for a number of years until it was discarded. Moreover, the team seemed to imply that the presence of the apparatus would somehow enhance learning, without much detail about what concepts would be learned or what type of questions the students would be expected to answer. Project 5 was very similar. The project was designed to demonstrate some important ME concept, but with no particular connection to a course. It was hoped that professors who taught related courses would use the equipment in a demonstration, or otherwise bring their students down to a lab to see the equipment in action. In practice, this was difficult to arrange if there was not a scheduled lab course attached to a particular lecture course. Furthermore, the equipment was not particularly mobile, which made classroom demonstrations difficult. Finally, with no particular pedagogical component, there was very little concrete evidence of exactly how these demonstrations would enhance learning. By not designing for learning, the students ended up creating large equipment that was doomed to languish unused. In contrast, all of the projects that consulted the pedagogical literature were adopted by the class.

Many of the projects that were ultimately not adopted by a class were developed without a close connection to a particular laboratory class. If they were not mission critical to the class, and required substantial work to finish them before they could be used for a lab class, they tended to languish and be abandoned. Also, if lab handouts and other teaching materials were not created or were inadequate, the experiments tended to be abandoned without a strong faculty advocate. Many of these projects were proposed specifically because the lab course instructor did not have time or resources to develop a new experiment. If the apparatus required extensive work or rework subsequent to the capstone design sequence, it was very likely that the prototype would be abandoned.

Student Interviews

Students who had finished their capstone experience in Fall 2014 were interviewed to determine their views about lab experiments, their prior knowledge about the pedagogy of teaching and learning, and how they had used the pedagogical literature in their design. The questions were designed by the lead author to allow students to reflect on their experience after finishing a successful lab design project. These questions were administered by a research assistant after the term had ended and the responses anonymized prior to analysis. Three students provided answers to the interview questions and the answers provide some insight into what students find valuable in lab experiments as well as their perceptions of pedagogical research. The three students had been working on a project to redesign a lab for a course in internal combustion engines that had become dated and somewhat non-functional. The initial lab equipment had been designed by capstone teams during the 1990's. A second team will be working during the Spring 2015 term in order to further develop new experiments to renovate the lab. The authors recognize that the number of interviews is extremely limited. This was due to the difficulty in contacting students who had already graduated. Nevertheless, some insights were gained into the thought process of these students.

The students were asked to describe their best lab experience as a mechanical engineering student, and what made it the best. In both cases, the students preferred hands on interaction with real tools, sensors, and equipment. One student enjoyed a lab in mechanical testing because it was "hands-on, exciting, and mildly dangerous". The other student enjoyed a measurements and analysis lab because it allowed him to learn to use tools that would be useful in the future. The last student talked extensively about working collaboratively, on material that was concretely connected to the course goals. These sentiments have been seen in lab surveys administered by one of the authors for a number of years as well.[12] Students strongly desire hands on interaction under conditions that are as realistic as possible. The students interviewed for this paper seemed to have understood this desire, and worked to make sure that the experiments they developed reflected current technology and realistic conditions.

Another question asked if the students were aware of the scholarship of teaching and learning before they did their capstone project, and what they knew about how instructors developed lab courses. One student reported being completely unaware of the scholarship of teaching and learning. Another had completed a previous project on the "benefits of experiential learning in an engineering curriculum". The student further explained that "I hadn't done much specific research into laboratory learning, but when doing research I was able to refer back to my experience with experiential learning." The third student had initially been a neuroscience major, and thus had taken a psychology course where he had been exposed to various learning and cognition theories. However, the idea of using these theories to design lab experiments hadn't occurred to him.

Perhaps the most informative responses were given in response to the question "Give at least one specific example of how knowledge of pedagogical best practices influenced your design choices." The student who had not been previously been aware of the scholarship of teaching and learning said:

"Our research into laboratory learning objectives netted us with 7 main objectives to follow in designing our lab. One of these was learning from failure. This was extremely important to us because we didn't want to make the lab completely fool proof. Had we done this, there would be no opportunity for students to learn from their mistakes. The way the supercharger experiment works, for example, if the students do not correctly position the intake and exhaust throttle bodies, they will not be able to measure any pressure difference between the intake and exhaust."

The student who had been previously aware of pedagogical research, had the following answer:

"Knowing pedagogical practices, we were able to decide which experiments were effective from the previous lab. We also kept these best practices in mind when designing the new experiments. If we came up with an idea, we wanted to make sure that we added aspects that would fit our lab learning objectives. If we found that we couldn't add these items, then we would rethink the idea."

The final student had the following to say:

"Before beginning to design anything we took a look at what the professor was teaching in the course. We felt like there was a very solid syllabus, all the important topics were being covered – however they were being covered in a demonstrational way. We aimed to take this to the next level and provide a more kinesthetic experience. The group combed through many articles on education and lab design. We looked at the experimental learning cycles that bring the classroom and the lab together, as well as learning objectives that classify the purpose of each experiment within the lab. Using these theories we were able to superimpose them and build a backbone for the lab design. Finally we wanted to bring something that we had never encountered before in a lab – and that was beauty. We believe that the lab should draw in the student and draw out their curiosity"

The student responses indicate that even when students are not familiar with pedagogical concepts, they can see the benefits of incorporating these ideas into their design process. It is important to note that this group, as well as other groups that incorporated pedagogical concepts, did not necessarily seek out these sources of information on their own. In most cases, they were initially guided to investigate the educational literature by one of the capstone design advisors. However, groups that really embraced the value of the educational literature found it helped them justify their design choices, and gave the students context for their solutions. They weren't just building a piece of equipment to stick into a lab – they were constructing an experience for their fellow students to enhance their learning.

Conclusions

When done correctly, lab equipment design projects can be beneficial to the capstone design students, the department, and individual courses. Students are often surprised to find that there is an enormous body of literature on how to design lab experiences to optimize learning. Once this discovery is made, students can and do use this information to improve their designs.

However, the best design will be a waste of effort if the equipment is never used. Projects with a strong connection to an existing or developing course, with a strong faculty advocate connected with the course, are much more likely to be adopted long term. Many of these projects tend to have cost, space, and infrastructure limitations imposed on them as part of the initial problem statement. A successful project that is connected with both a course and with the particular lab space the course uses can be very easily integrated. For large commercially available equipment, the space must be altered to adapt to the equipment, rather than building the equipment to suit the limitations of the space. Projects which are completed with no particular course or space in mind tend to languish unused. Capstone design instructors and lab personnel who are looking for custom, low cost experimental equipment should consider making this a challenge for capstone design students, provided a strong course connection and supportive faculty member can be found.

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