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Improving the Learning Process of Laboratory Instruction

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Abstract

There is little doubt that a laboratory experience can be beneficial in the learning process of undergraduate engineering students. Relating the textbook and the lecture to hands-on observations can help resolve inhibitions in concept perception and produce clarity of key issues. Unfortunately, time constrains faculty development and execution of laboratories and can reduce this potentially beneficial experience to little more then conducting tried and true experiments semester after semester. As a result, students find old laboratory reports to be an equally expedient at fulfilling assignments leading to lot of busy work that neither the instructor nor the student benefit from.

This paper will overview approach, application, and benefit of abandoning the cookbook approach to conducting the undergraduate laboratory experience. The concept relies on the undergraduate students, working in teams, to design and conduct experiments. The instructor acts as a mentor and resource during the process, and insures quality of the laboratory exercise without having to be the sole responsive party. By taking ownership of the experiment, the students' learning is increased and the laboratory experience is enhanced. This is due, in part, to experiments being tailored to the students' needs and interests which is a result of their direct involvement. Finally, concepts of team building and experimental design are introduced. Surveys and testing of students involved in this approach suggest a strong positive outcome. In addition to objective outcome assessment of participating groups, several years of applying this approach have defined pitfalls to be avoided.

Introduction

An issue impacting the undergraduate laboratory experience is the enormous financial pressure faced by engineering departments struggling to address increased enrollments, static budgets, and the desire to maintain educational quality.[1] Hands-on laboratories are typically expensive to develop and support. Involving faculty in this activity generally reduces departmental productivity as laboratory classes produce fewer credit hours for the amount of contact time required.

Still, there is little doubt that a laboratory experience can be beneficial to the learning process for undergraduate students. The opportunity to relate the textbook and the lecture to observations made during a hands-on experience can help resolve inhibitions in concept perception and produce clarity of key issues. Unfortunately, time constraints and productivity demands on faculty trying to develop and conduct laboratories can reduce this potentially beneficial experience to little more then a set tried and true cookbook experiments used semester after semester. This situation is generally exacerbated by using graduate teaching assistants (GTAs) as a labor saving approach. Often these individuals have little motivation to put forth more than a minimum effort to see that students attend labs and submit reports for quick grading.

This situation is compounded by the prevalence of linear thinking on the part of many faculty involved in undergraduate engineering education programs. Such instructors presume that knowledge gained is directly proportional to the volume of assignments completed outside of the classroom. While this is true if the level of work demanded of students is low to moderate, the productivity demands placed on undergraduates today can evoke a shift in the learning process where learning is actually diminished in favor of getting assignments submitted.[2] In short, undergraduates often perceive themselves as having excessive demands on their time, ability, and resources as a result of spending numerous hours on repetitive homework and cookbook laboratories.

Most processes function in a "nonlinear" manner, meaning that two or more stimuli affect a system and the subsequent response is not simply a sum of responses to the individual stimuli. `In spite of this fact, mathematical and procedural tools for dealing with simpler, linear systems are generally taught. This is in part because students struggle with uncertainty. They expect the instructor to know the answers beforehand. Hence, there are two hurdles to cross: getting students to feel tolerant of uncertainty in order to live with and even enjoy the search for a research result and getting students to accept that it is normal for there to always be a single, definite answer to every problem.[3]

Unfortunately, some instructors prefer to constrain topics presented to students to those that are absolutely familiar or predictable. This reduces what occurs in laboratory to a parody of learning where students “cookbook” the experiments and regurgitate the same relative results semester after semester. Once old laboratory reports start circulating, the process degenerates to one of knowledge mimicry rather than knowledge acquisition.[3] In this environment, the student forgoes cognitive processes for the sake of making the deadline. The result is what Bella[2] refers to as a “plug and chug” mentality towards outside work. The plug and chug approach to completing assignments allows you to get by without wasting time thinking, does not require the student to really understand what they are doing, and even protects their limited knowledge of the subject from being exposed. This accommodation leads to a narrow focus upon assignments to the exclusion of inquiries, questions, and efforts that do not directly contribute top the immediate demands being faced. In terms of laboratory exercises, resourceful students find old laboratory reports an expedient solution to fulfill lab assignments and the end result is a minimum of learning and a lot of busy work from which neither the instructor nor the student benefit.

Students learn best when they are actively seeking the information they need to accomplish a learning task. They play the role of researchers and navigators rather than spectators. They use higher-order thinking and act as problem solvers in the learning process. The teacher no longer is the "sage on the stage" but rather the "guide on the side." He or she facilitates learning rather than controls it. Students can no longer be expected to absorb a static set of facts, because those facts soon become obsolete as the rate of new discoveries accelerates. Students "construct" their own knowledge as they come across various information resources. This means they must develop process skills that allow them to investigate, classify, evaluate, and communicate information.[4]

Course Objectives

An obvious solution to the problems of the cookbook laboratory experience is changing the experiments performed each time. However, there is an opportunity provided in this dynamic beyond just developing multiple, interchangeable subsets of predictable laboratory exercises. Specifically, with nominal effort on the part of the instructor, the undergraduate students can be exposed to an open-ended learning experience that also helps develop student skill sets outside of just the technical material being addressed.

Under the traditional teacher-centered educational pedagogy, the academic-as-teacher was totally responsible for design and delivery of courses with graduate teaching assistance often provided to assist the instructor and students. The exercise is generally designed based on the instructor's knowledge of expected outcomes and research approach accuracies. A student-centered approach to learning requires an approach in which the instructor becomes guide, coach, motivator, facilitator and coordinator of learning resources. This requires a context of learning which encourages students to actively engage in the subject matter.[5]

In this environment the student becomes a more active participant having to analyze, question, judge, and combine ideas and information in order to define and solve problems. Learning and teaching activities for a student-centered learning process requires a more complicated designing process that enables students to contribute their knowledge to the learning environment. It leads to group projects that encourage consideration of peer knowledge, to action-based learning, and finally to the use of work-integrated learning in which students are asked to reflect on theory in terms of their experience.[5]

Integral to this process is an effort to provide a learning experience that meets the educational needs of the student from a technical perspective. In fact, this author contends that the laboratory design can address several of the accreditation process mandates. Specifically, accredited programs must demonstrate that their graduates have:

- an ability to apply knowledge of mathematics, science, and engineering (ABET Criterion 3a),
- an ability to design and conduct experiments, as well as analyze and interpret data (ABET Criterion 3b),
- an ability to design a system, component, or process to meet desired needs (ABET Criterion 3c),
- an ability to function on multidisciplinary teams (ABET Criterion 3d),
- an ability to identify, formulate, and solve engineering problems (ABET Criterion 3e), and
- an ability to communicate effectively (ABET Criterion 3g).[6]

To facilitate the process, one should recognize that classroom discussion, collaborative teaching and learning, and cooperative team experiences are required to aid in the development of critical thinking skills of undergraduates. They prefer group interaction, teamwork, and the opportunity for input. Results suggest that such classroom learning environments were found interesting, informative, and effective. They even promote professional development of the students in the areas of self-confidence, communication, and leadership.[7] These findings, and others, are why the National Science Foundation, the National Academy of Engineering, the National Research Council, and the others have worked to define a new engineering education paradigm that includes:

- integration of subject matter, concepts, issues and principles including to subject matter covered previously,
- emphasis on inquiry-based learning and preparation for life-long learning with less dependence on lectures,
- stress integrative, systems thinking, coping with change, communications skills (listening, speaking, reading, and writing), teamwork and group problem-solving skills (from problem identification through analysis and resolution).[8]

Requiring students to work together in groups encourages extroverts, who enjoy interaction with others, to study and learn more while introverts benefit by developing teamwork skills. Of course, freeloading can be a problem, but one that can be handled by requiring the teams to rate the performance of its members.[9] Input for students conducting the lab is another quality and participation check as are the observations of the instructor and GTA. If students know their going to be held individually accountable for the final product, most will make a serious effort.[10]

There are also several reasons why a team approach might fail. Lack of commitment by the instructor, GTA, or students results in infrequent meetings, lack of course resources, and an unsatisfactory laboratory experience. Poor communications between instructors and the student team can serve to lead to missed goals, misdirected efforts, or inadequate preparations. Further, if the student reward system is inadequate, motivation of the members will be low and outcomes less than desirable.[11]

Motivating student behavior is complicated by individuals having their own unique value set developed by previous experiences and subjective interpretations of past events. Each student brings a unique perspective to a team. Hence, each interprets events differently and in relation to their goals and the perceived value of anticipated outcomes.[12] Providing an opportunity for individual and collective input into the educational process helps obtain student buy-in and increase the likelihood that the team experience will be a success.

Taking all of this into consideration, the environmental laboratory experience provided an undergraduate student in the civil engineering program at Mississippi State University was redesigned around the use of undergraduate student teams. The number and size of teams was dictated by class size, which generally ranges between 45 and 60. Each team consisted of between six and eight students and each class was divided into seven or eight teams. These teams would serve as "Lab Captains" for experiments that they elected to design for a class-approved list as defined below.

Each team of Lab Captains was charged with the design, set up, instruction, monitoring, and data compilation of a lab to be performed by their fellow students. The team was responsible for developing handouts, constructing apparatus, arranging transportation, making up reagents, and all other activities required to conduct the lab. They were also required to develop a solution to the lab, but this was provided the instructor as a key for grading the lab reports submitted by the rest of the class. To facilitate this process, a faculty member and a GTA worked with the group.

Course Design

At the outset it was decided that the environmental laboratory experience would provide undergraduate students with more than how to perform analytical tests. It was acknowledged that students should know how to accurately characterize water and wastewater samples. However, the benefit of such an effort was deemed minimal in comparison with the opportunity to expose the students to environmental management issues and treatment operations and processes.

To increase student interest in the laboratories conducted during the semester, a class-approved list of research topics was developed. At the outset of the semester, a list of potential research topics was distributed to the class. Each was reviewed in the context of the topic's relationship to environmental engineering. Students were then asked to vote for the top two to four topics they wanted to research during the semester. Those topics receiving the most votes, plus those the instructor felt were required to cover the appropriate course material, and compiled into the class-approved list and was used as a basis to design the semester's laboratory experience.

During the second class meeting, the teams of Lab Captains were developed. The list of class-approved topics was distributed and the students were asked to select the topic they would be interested in working on as a Lab Captain. The number of students on each experiment design team was limited, as indicated above, so that each group had approximately the same number of members. By having the students pick several topics during the list development process, it was felt that each student had a reasonable chance of selecting one of their preferred topics. Once the teams for each topic were selected, the final schedule of laboratory exercises was developed by the instructor taking into account academic calendar, seasonal variations that might impact research opportunities, and infrastructure limitations as related to the selected topics. Scheduling was delayed until the teams were established in anticipation that some students would choose labs scheduled late in the semester rather than labs in which they were interested.

About two weeks before the laboratory exercise was to be performed, the team met with the faculty member and the GTA. During this meeting, the faculty member defined specific tasks and deliverables for the team. The group discussed the topic and possible laboratory experiments. Samples of old lab handouts were provided and ideas were discussed about experiments that could be performed and related to the classroom lecture. Laboratory facilities and equipment opportunities were summarized for the Lab Captains as this often contains what experiments can be developed or the level of effort the team will have to expend to construct needed experimental apparatus. Taking all of this information, the team would defined and develop a specific laboratory exercise related to the topic they had selected.

At this point, the graduate teaching assistant became the primary point of contact. The students worked through the graduate teaching assistant and the instructor to prepare the lab. A dry run of the experiment was highly recommended, but not required, as the students grade for developing the lab was based on the way the lab went off. They were aware that problems arising during the lab, or with the lab handout and the class report preparation, would reflect badly on their grade. At the same time, a draft laboratory handout was required of the team for review by the instructor and GTA at least two days before the laboratory class met. This draft gave an opportunity to insure progress on excise design and the quality of both the experiment to be conducted and the handout. In short, it was an aid in helping insure the team was ready in advance for the class with an experiment that was reasonable and appropriate for the topic.

To prepare the exercise, the team was responsible for assigning workload and task. As typical of many teams, some individual put more effort into the project then others. Some preferred to focus on developing handouts while others would assume the responsibility of setting the laboratory equipment up or arranging for field data collection. However, each member of the team was required to participate as a Lab Captain on at least one of the days that the experiments were performed by their classmates,

Though the activities of having the laboratory exercise were the responsibility of the assigned team, the instructor or the GTA were present during the laboratory class. While this was partly a safety issue, it also provided an opportunity to evaluate lab preparation and general performance of the team of Lab Captains. Observations made during this time were directed at determining if each team member was prepared and knowledgeable of the experiment. The level of involvement of each Lab Captain in supervising experiments was also noted as a way of identifying team members who had put extra effort into the process. Finally, while some Lab Captain involvement in the exercise was expected, the experiments were not to be demonstration activities and too much involvement by the team was deemed an indication that the lab was not properly prepared. All of this information was used by the instructor in assigning a grade for the student team responsible for the laboratory and for individual Lab Captains.

Immediately following the class, the Lab Captains were responsible for compiling and distributing the data. Often, data from several sections of the class held on different days over the week were combined to allow evaluation of more data and greater variations in experimental design with less work on the part of their classmates. Once the data set was compiled and distributed, the team of Lab Captains provided the instructor with the solutions key.

Performance Assessment

To evaluate the effectiveness of this approach to developing and teaching an undergraduate environmental engineering laboratory, a survey was conducted of the students. To help validate the data collected, two experiments were added during the semester using the traditional approach of having the instructor develop, prepare, and supervise the class activities.

Initially, the survey was administered following submission of each laboratory report by the class. However, it was determined that the class had difficulty maintaining perspective of how well one laboratory experience related to another. So, a comprehensive survey at the end of the semester was adopted. Several of questions were asked regarding the approach of using undergraduates to develop and conduct that lab exercise. These questions are presented in Table1. Others were directed at the overall laboratory experience, as presented in Table 2.

Table 1. Laboratory Captain Experience Evaluation

Compare using class members as lab captains to the traditional approach of having the lab handed to you by a graduate student or professor.	Yes	No
I like doing the labs this way?		
I feel there was too much expected of lab captains?		
I feel the lab quality suffered because undergraduates were used this way?		
I wish the class could have reviewed experiments as a group instead of letting the lab captains decide what we were going to do.		
I think you learned more doing labs this way?		

Table 2. Laboratory Course Evaluation

Evaluate this semesters lab experience	More	Just Right	Less
Number of laboratory experiments?			
Number of field trips?			
Number of indoor experiments?			
Help from Professor and Grad Student in preparing lab exercise?			
The information learned for time spent compared to other CE labs?			
The information learned for time spent compared to non-CE labs?			
Time spent on lab reports compared to other CE labs?			
Time spent on lab reports compared to other non-CE labs?			

In addition to the process, this survey provided an opportunity for the students to give feedback on the lab captains and the experience they had with each of the experiments. They were asked to rate each laboratory with regard to the following statements:

- The lab seemed to be well thought out.
- The lab was properly set up (prepared) beforehand.
- Lab handouts were well prepared and clear.
- Handouts were available on time.
- The experiment was interesting.
- Questions and problems were reasonable.
- Data from labs were available on time
- The effort was educational and instructive.

- My level of effort in lab was reasonable
- I think this was a good lab for us to have done.

As part of this process, they were required to identify the exercise for which they had served as a Lab Captain. While this data was used to establish part of the Lab Captains' grades, it also provided a comparison of the traditional approach as two of the experiments were conducted by the instructor and the GTA in the conventional manner.

Analysis of Results

It was found that topics presented to the student should have a broad format as the students had basically a layman's knowledge of the field. Using environmental management terminology rather than proposing specific processes consistently attracted the most votes during the laboratory formulation process. Examples of topics preferred by students included:

- Evaluation of Dissolved Oxygen in a Mechanical Wastewater Treatment System,
- Monitoring Water Treatment Facility Performance,
- Analyzing Stratification and Water Quality in Flowing Water, and
- Managing Organic Pollutants.

Topics that would have led to the same experiment, but were not well accepted by the students included:

- Aeration and Gas Transfer,
- Filtration,
- Stream Velocity and Dissolved Oxygen Measurement, and
- Carbon Adsorption.

From this, it was concluded that students were able to identify with environmental issues. Interviews with students also suggested their avoidance of process experiments was a result of their anticipating the technical difficulty of the experiment and perceived lack of ability on their part. Further, it was learned that students welcome an opportunity to leave the indoor environment to perform experiments. As such, topics that appeared to require field trips were preferred over those that were presumed to require inside experimentation.

Combining the data for four years of laboratories conducted using this approach, we have found that students consistently rate overall laboratory experience higher if students are involved and have done a satisfactory job of developing and conducting the class. Only if a team of Lab Captains is unsuccessful in developing and conducting a laboratory experience does the lab rate lower than a traditional cookbook experience. Review of the data indicates that lack of preparation by the team is the primary reason for this occurring. In general, this occurs when:

- The team feels that a dry run is not required to insure things are set up properly,
- A field collection site requires too much time to get to for that amount of data collected,
- A contingency was not developed to address the event that field conditions changed from what the Lab Captains had expected, and

- Equipment, instruments, transportation, or apparatus required for the experiment failed and a contingency for the failure was not available.

Regarding the overall experience of using laboratory teams and the Lab Captain approach, the data collected are summarized in the following tables:

Table 3. Laboratory Captain Experience Evaluation Results		
Compare using class members as lab captains to the traditional approach of having the lab handed to you by a graduate student or professor.	**Yes**	**No**
I like doing the labs this way?	98%	2%
I feel there was too much expected of lab captains?	10%	90%
I feel the lab quality suffered because undergraduates were used this way?	23%	76%
I wish the class could have reviewed experiments as a group instead of letting the lab captains decide what we were going to do.	11%	89%
I think you learned more doing labs this way?	79%	21%

Table 4. Laboratory Course Evaluation Results			
Evaluate this semesters lab experience	**More**	**Just Right**	**Less**
The information learned for time spent compared to other CE labs?	28%	62%	10%
The information learned for time spent compared to non-CE labs?	54%	46%	0%
Time spent on lab reports compared to other CE labs?	33%	52%	15%
Time spent on lab reports compared to other non-CE labs?	50%	36%	14%

It would appear that the students overwhelming preferred the opportunity to design the laboratory experiments. Further, the students felt that the approach has a reasonable time commitment for the information and experience gained from it. It can be presumed, in part, that this experience also improved the learning process as based on student evaluation.

In a more subjective process, evaluation of student performance on examinations during the lecture class associated with the laboratory appeared to improve as a result of the process. Due to faculty and student networking on the design of the experiment, it was easy to relate the experiences of the laboratory experiment to the student observations. Specific opportunities were developed if the laboratory schedule was carefully crafter so that topics covered in lecture occurred at about the same time in the semester as the lab. While this is certainly possible if the conventional approach is used, the buy-in by the students appeared to enhance discussion during lecture periods.

Summary

In this time of limited educational resources and high expectations for the total quality of the undergraduate student experience, using the undergraduates as a resource can help with the success of the laboratory experience. The approach also allows faculty and students to interact to their mutual benefit. However, employing teams of students to serve as Lab Captains is more than having extra hands to help set up a laboratory exercise. It provides them with an opportunity to experience experimental design first hand. It exposes them to team work and the problems and benefits associated with such a solution approach. It helps them focus on what they will study and allows them a closure exposure to a topic that would otherwise be just pictures and word in a text or a lecture. In short, this "buy-in" by the students in preparing a topic of their choice increases their interest and performance. Finally, the experience of designing and conducting an experiment is consistent with the ABET criteria by which departments are being evaluated.

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Biography

DENNIS D. TRUAX is a Professor of Civil Engineering at Mississippi State University. He has over twenty-five years in education, he has more than 80 published papers and reports and over 110 paper and poster presentations. Researching and consulting in the areas of wastewater and watershed management, he has worked on projects through out the United States as well as Canada, Mexico, China, Romania, and Turkey.