Problem Based Learning in a Chemical Engineering Undergraduate Laboratory

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Abstract

We have recently revised our undergraduate chemical engineering laboratory curriculum, space, and equipment. Specifically, Problem-Based Learning (PBL) methods were applied to experiments. The decision to do so was a result of several motivating factors. Some of these factors were pedagogic in origin, others stemmed from our desire to add flexibility and variety to our experiments, and others were a response to ABET's *Engineering Criteria 2000*. Our new focus combined previous efforts in engineering science fundamentals with open-ended and economically driven problems. These problems aimed to enhance student learning while developing interpersonal, problem solving, learning, and communication skills. PBL and our expanded expectations resulted in improved behavioral and skill outcomes. We argue that the Problem-Based approach was particularly well suited to laboratory application and should be considered as a model for replacing traditional laboratory methods. This paper presents preliminary results in the form of our observations, shares some perceived issues regarding the implementation of PBL, and discusses student reactions to a PBL course. In short, this paper offers an evaluation of the learning outcomes achieved and presents some insights gained by our experience.

Introduction

Historically, the educational goals of our laboratory focused on having students employ and verify theory learned in core courses. Feedback from our alumni indicated they appreciated the strong fundamentals that our laboratory instruction helped them learn. However, both alumni and ABET[i] seem to agree that new industrial processes and the modern work environment demand that students should be able to apply fundamentals to a wide variety of problems. Further, graduating students must be skilled communicators, possess strong problem-solving skills, have the ability to design systems and experiments to meet given needs, and should understand the context in which their work will be practiced. One question that arises from these desired outcomes is "How will all of this be accomplished most effectively?" Moreover, concern existed over whether explicitly teaching these skills would come at the cost of sacrificing technical material.

One step we have taken toward achieving these outcomes was to amend the educational philosophy, objectives, and pedagogy of the lab courses. The goal is now for students to develop desired skills while reinforcing fundamental knowledge. Specifically, we have implemented Problem-Based Learning in order to foster specific behaviors. Students worked on open-ended problems in the laboratory courses and gained desired skills by:

- solving open-ended research, design, and development problems.
- designing experiments to reveal controlling physical or chemical mechanisms.
- linking the needs of problems to economic, scientific and engineering criteria in order to define what data to collect as well as what errors are acceptable.
- seeking information from a wide range of sources.
- working in teams.
- managing projects in the absence of supplied time constraints.
- developing a "hands-on" approach in the solution process.
- acquiring and respecting "physical intuition" in engineering practice.
- developing their interpersonal skills.
- gaining confidence in their problem solving abilities.
- submitting extensive oral and written reports.

Though PBL was originally used in educating students in health professions, the use of PBL has grown significantly at many levels of education.[ii] The application of PBL to undergraduate engineering programs has been increasingly common in recent years, Monash University and the City University of Hong Kong being two examples. While engineering education, almost by definition, aims to enable students to contrive solutions, it would be incorrect to label most engineering educational methods as "problem-based." That is, learning how to solve problems is not the same as Problem-Based Learning. Indeed, many engineering programs have introduced "industrial" or "good engineering" practices into their laboratories. For example, the University of Missouri's Chemical Engineering department felt that their laboratory courses should encourage students to get results while also teaching them to write concise reports. In short, lab should not only demonstrate theory. As a result, they replaced simple theory-based goals with "practical, industrial problems."[iii] Although this change incorporated many of the ideas of the PBL approach, it is learning through problem solving that defines PBL. This approach not only allows important knowledge to be gained, but it also passes along indispensable skills.

Our Implementation

Although PBL often improves the quality and nature of student learning, these gains may be attained at the cost of less material being presented in comparison to Subject-Based Learning. As such, PBL was deemed an excellent option for the laboratory courses because little of the laboratory material was new. So, open-ended problems consisting of design and research & development problems were drawn from local industry and from general industrial production, research, and development situations. The course structure follows:

The lab course is 2 credit hours, and typically slightly less than 50 students enroll. The class forms teams consisting of 3 or 4 people. These teams get divided among 4 different lab days. Groups are in lab 3 hours per day, one day of the week. In addition,

the entire class meets for a one-hour lecture once a week. These lecture periods have been used to prepare students for the PBL approach and are also used for the students' oral presentations.

Each team works on two problem-solving projects during the semester, where each project covers 6 weeks. Students are supplied with a problem statement, MSDS sheets, and various other resources. At both the midway point and the end of the project, each group presents a 15-minute oral report and submits a written report. The midway reports serve as proposals based on initial findings. In this proposal students outline a plan for how they intend to solve their particular problem. The final reports summarize their approach and findings and conclude with recommendations.

Also, at the end of the first six-week project, each group trains the team that will continue working on their problem. In the training session, the first team instructs the second team on the operation of the equipment and on how the project can be extended or improved. The first group also introduces basic theory and explains where they may have failed in solving the problem. The second teams verify data from the training team to see the principles clearly and to insure they understand the equipment, the problem at hand, and other important considerations prior to working on the problem.

An Example Case

Exactly how this approach has been applied to our classical pressure drop in pipes and fittings experiment follows. This experiment previously involved calibrating instruments, measuring flow rates and pressure drops, and then calculating and reporting friction factors, velocity profiles, etc. The data acquired was compared with textbook predictions and handbook values and differences were noted and discussed.

The problem-based approach asked teams to recommend a pipe system and concentration of drag reducing agent (PEO) for use in transporting a large volume of wastewater over a long distance. Groups were given basic help in getting started. Although the first week in lab focused mostly on the fundamentals, students began working on their problems immediately. After a few weeks, groups had calibrated "base-case" data and understood the essential aspects of their problems. Within these first weeks, lab groups commonly made the following discoveries: the drag reducing agent was degraded by the pump in the recycle loop, more accurate calibration of the equipment on water was needed, "high" concentrations of PEO or degraded PEO actually increased the pressure drops, or even that PEO was not allowed in their waste system. As a result, many groups concluded the apparatus did not allow them to draw sound conclusions. Shortly after being told that coming to "no solution" was not acceptable, groups innovated. For example, one group found designs used in government and academic research. Based on these, the groups constructed a simple apparatus that solved the "recycle-degregation" problem. As a result of their studies, students learned both the fundamentals of turbulent flow through pipes and how drag reducing agent could be applied and used in the "real world." In doing so, they performed extensive literature searches, worked in teams, collaborated with other teams, presented their results both in oral and written format, grew in setting up and designing experiments, performed applied engineering economics, sized and purchased an injection pump, and learned how to sweat copper pipe.

Important Factors in Implementing PBL

Equipment considerations proved to be key. Equipment flexibility, failures, and mobility were three facets of particular importance. First, as the problems created often required extensive changes to the equipment configuration, more work and time was spent insuring that equipment could be altered appropriately. Second, equipment failures, though at times troublesome, proved to be mini-PBL projects. Although these were frustrating, students often found "troubleshooting" equipment to be a rewarding activity. Finally, the ability to move equipment has proven useful. Upon the adoption of PBL, all of our equipment was put on rollers or was made mobile. Such mobility allowed for the full utilization of lab resources. Students often demonstrated the need to look beyond their own equipment. For example, a group working on soil remediation needed a quick means of testing saltwater concentration. Students adapted portions of another lab to measure their samples' conductivities.

In addition to experimental demands, PBL has caused students to need more support. This has largely manifested itself in two ways. First, this has meant providing students with better computer and analytic tools. Second, students have required improved access to information resources.

As a result of the first problem, we added networked computers in the lab. This has not only enabled students to analyze data as they collect it, but has allowed students to modify their experiments and procedures more quickly.

The issue of how PBL has increased demand for specific information and resources resulted in several changes. In some cases interfaces to the experiments for data acquisition and control were created.[iv] In others, developing WWW support for PBL helped.[v] To date, our primary effort in aiding students in information retrieval has been to provide them with a packet outlining the resources available through campus libraries. Additionally, over the last two years we have built a reference library in the lab consisting of books, two file cabinets of journal articles, previous years' laboratory reports, etc.

Observations of Desired Outcomes

We observed the behaviors of our students to try to detect if this approach was effective. Our preliminary results indicated that students who experienced problem-based learning in our laboratory displayed a wide variety of responses. We have been monitoring student progress and are currently developing measurement tools for the desired outcomes. The following section offers our observations with respect to a variety of topics.

Prior to the new course structure, students were asked to do little more than to follow a recipe. Problem-solving skills have been a new priority, with students translating open-ended problems into detailed experimental plans. We have observed a switch from "read the recipe in the lab manual and do what it says" to "think about the solution of the larger open ended problem, perform some preliminary calculations to determine the important features of the problem and then plan the important experimental steps." Initially, students were hesitant to develop a solution without consultation with one of the course instructors. As the course progressed, students increasingly grew independent in solving even basic problems. For example, one lab involved acquiring four thermocouple readings simultaneously where only one was available. Students

simply altered the equipment as needs demanded. As simple as this was, it represented an especially large behavior change.

Previous error analysis was limited to basic error propagation and little thought was given to what constituted “meaningful” data. PBL brought about more capable performance in error analysis as the analysis has been linked to problem needs. That is, with PBL we observed students reasoning that a particular flow rate measurement was (or was not) accurate enough given the decisions they had to make in order to reach informed conclusions. Essentially, the behavior observed has been the more effective use of primitive statistical experimental design concepts in formulation the experimental plan and final analysis.

We also have seen increased intuitive awareness of how changes in controlling variables create changes in mechanisms or output. One student summed this up in remarking “I just somehow know the sensitivity and the orders of magnitude...” One positive result of this change was that we detected more 'mechanism speak' in students’ oral and written reports. For instance, reports described controlling mechanisms such as 'diffusion limited vs. convective flow limited' through a membrane.

Additionally, students previously were given most of the information they needed. Consequently, students were unaware of the resources available to them. We find the nature of PBL led students to search a wide range of information sources; the searches reached beyond searching textbooks or laboratory manuals.

Another significant impact of PBL can be seen in the approach of the course; students were given previous years’ reports and asked to cite prior work. Before, the prior reports were either not available or were obtained from a student organization file. As a result, they displayed more concern with the validity of information they read. That is, they compared these reports to their approaches and results and scrutinized discrepancies more carefully. Further, students realized they were no longer writing for just the course instructor. These are reasonably large changes in student behavior. Students saw first-hand how hard and important clear and concise writing is.

Just as with written reports, significant changes were seen with respect to oral presentations. While other courses typically required one or two oral presentations, we felt this did not develop the confidence and technique needed to generate effective presentations. In addition to the required 4 presentations, a one-page evaluation and comment form was filled out by each member of the class during the presentations. Teams summarized the class comments, discussed the comments, and formulated action plans for improvement. Since the projects were passed from team to team as the semester progressed, the questions from the peer audience were often very challenging. Also, as multiple teams often “competed” toward a solution for the same problem question sessions were very active. Since adopting these oral report practices, students have improved significantly during the semester.

Another curriculum issue reviewed focused on when students receive design experience. Prior to their senior year, most students get little or no preparation in modeling and design. PBL pushed students to develop 'new' theories or models that were appropriate for the problem – in their junior year. In some cases, students have gone so far as to combine first-principal models with statistical correlations to obtain models that

are appropriate for the problem being solved. For example, in a problem involving the viscosity of water-contaminated motor oil, the students tried to extend the Stokes-Einstein model with a statistical correlation to describe the viscosity behaviors. While this was advanced work, we believe that students should be allowed to "bite off more than they can chew" to some extent. Regardless, students said they "learn more, despite the fact that design is next year."

As a final observation, student attitudes towards groupwork have changed. In the past, teams split up responsibilities and tended to interact only when responsibilities overlapped. As students face the challenges created by PBL, they realized they could only solve problems as a team. Students accustomed to surviving on individual effort found themselves struggling. Also, an increased amount of technical discussion occurred as students enjoyed the process of working towards these "larger" problem solutions. Students appreciated the opportunity of having responsibility for problems that linked to their ideas of engineering practice.

Problems and Concerns

The biggest problem incurred in the switch to PBL was the added support PBL required of course instructors. Asking students to tackle so much had inherent problems. Primary problems included providing sufficient information and guidance, performing equipment alterations, defining the problems for PBL usage, adjusting the added time demands, counseling students on the nature of open ended problems, providing adequate feedback, and assessing performance.

Supporting students proved difficult as we did not fully anticipate their needs. Though to some extent a natural part of PBL, student background rarely proved sufficient. Specifically, juniors have not taken all the coursework they need to deal with some of the issues. For example, when students set out to perform cost estimations, they found they had to learn how to do much of the work. While this has increased student independence and confidence, ill effects accompany it. One such effect of this background deficiency was that added student workload was created. The time spent providing the support students needed was troublesome.

Where the previous style of laboratory experiments required little or no literature or information seeking, PBL often achieved the goal of encouraging students to synthesize a variety of disciplines. As a result, students often found themselves searching for information. For example, groups solving a problem concerning remediation of contaminated soil needed EPA data, information concerning mass transfer models for mixed media systems, etc. To date, finding this support documentation has been the students' task. While the skills that accompany this were skills we wished to encourage, support in where to look needed to be developed.

Another concern has been the time this course has consumed in planning, running, etc. PBL demanded more from the faculty than when students all did the same, static experiments. However, we felt the additional time was justified by the results of having students practice the skills required to solve these types of problems. We are investigating ways for using the student teams to work cooperatively to reduce some of this faculty and staff time demands. Our belief at this early stage is that, with time, we

will improve our understanding of PBL issues and gain insights as to how to streamline the class.

Finally, the pre-PBL instruction styles allowed for uniform and clear performance assessments to be made. In our PBL implementation, members of a team share the bulk of their grade based on the team's process for solving the problem. While this placed importance on the process students used, this does not imply the process to be more important than the knowledge -- to the contrary! For indeed, as Don Margetson points out, "the question is not whether knowledge is vital...but how students will best come to gain and understand it thoroughly. The process of PBL is carefully structured with the intention that students learn well, not simply by being told things, but by learning to pursue inquiry effectively."[vi] We tried to monitor both how well the problem was approached and how well fundamentals were understood. This was done by having students report on both aspects and also by setting up formal means of evaluation. To aid in assessment, we included self and peer-evaluations, assessment of team's training efforts, and small prelab assignments. In the end, students saw how well they performed in relation to their peers because of the extensive amount of presentation and result-sharing which occurred.

Student Reaction

Students were asked to respond in writing to a series of questions concerning PBL use in the course. Students were asked to rank lab objectives in order of importance; students overwhelmingly chose "gaining hands on experience and intuition" along with "learning to link theory to experience" as the most important objectives. These were ranked ahead of oral presentation skills, demonstrating theory, writing skills, and interaction with other groups, etc. In short, students appeared to desire an experience consistent with our PBL methodologies. These data served as encouraging feedback, though specific comments provided more insights. In general, assessing PBL proved difficult, although others have done extensive work evaluating medical school and other cases.[vii viii ix] The student assessments are summarized below.

In responding to a question concerning the workload of the course, phrases similar to "This is a two credit hour class and it takes more time in and out of the lab than my four credit hour classes!" were common. Students replied that "when we're done" was not clearly defined. As students were used to being able to know when an assignment was completed, open-ended PBL created difficulties. This was common, and students lamented not having a course where the problems had well-defined end points. Students simply did not know when to stop working.

While some commented on the workload, others concluded that the instructors "had no clue what [they were] doing." As the courses progressed students began to understand, though some students never "got it." A few students resisted the implementation of PBL and tirelessly complained about how poorly organized their labs were. These students were given more direction and were monitored for progress more carefully. In retrospect, we were at fault during the first year of implementation for not sharing with students more of the thought and philosophy of our actions. Our Faculty-Course Evaluations revealed student displeasure by having low scores. By our second attempt at PBL we had adopted materials to control this problem. Primarily, this meant the course staff explained PBL to students, discussed problem-solving techniques, had the

class perform some example problems, etc. In their teams, students are effectively asked to be cooperative learners. We feel, and Karl Smith of the University of Minnesota[x] would surely agree, that if you do not work with students specifically in this way, cooperative learning is far less likely to succeed. We also adapted materials from, and highly recommend, Donald Wood's excellent handbook, How to Gain the Most from PBL.[xi]

Part of the comments regarding course planning were related to "the uneven quality of the projects." Some projects were design problems involving relatively straightforward engineering models and economics and experiments while others demanded more. The later required 'new' theory or experimental approaches. Many students, depending on their aptitudes and dispositions, saw some labs as being "harder" than others were. This was important feedback as formulating appropriate and suitable problems was an important challenge faced by course organizers.

Finally, a variety miscellaneous comments were made. These included comments that students enjoyed the team accomplishment and took pride in discovering that they were capable of solving difficult and 'real world' problems. Finally, many students felt that PBL facilitated more ownership over their experiments. While not all of the feedback at the end of the course has been positive, the verbal feedback in the following semesters tended to be overwhelmingly positive.

Conclusions

The course objectives were made to incorporate larger issues of student development. By adopting an open-ended Problem-Based Learning approach, we observed significant changes in student behaviors. In total, the behavioral and learning outcomes were superior to those of our previous, non-PBL, laboratory courses. The gains came at the cost of increased work on the part of the faculty, expense in enabling the facilities to support PBL, and more workload for the students.

The problem statements proved hard to create and required more information support, but these trade-offs have been deemed acceptable given the gains achieved. Further, the majority of students looked favorably on their PBL experience. Nearly all students accepted the exchange of slightly more challenging work for the opportunity to enjoy their work, and most students felt as though they learned and grew. In addition, PBL proved to be more fun to instruct as each semester brought new problems. However, the benefit of increased instructing pleasure comes at the cost of more energy and resource expenditure with respect to previous practice. Finally, as the lab course did not aim to teach completely new material, the "slower" and "less controlled" flow of Problem-Based Learning does not have a negative affect. Given the gains made in students behaviors and skill sets that ABET 2000 calls for us to measure, we felt adopting PBL in the lab to be a useful tool. In short, we were pleased with the results of PBL and will continue our efforts to adopt PBL in our lab.

References

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Biographies

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