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Integrating Problem-based and Project-based learning in large enrollment freshman engineering courses

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Abstract

This paper reports on the integration of problem-based and project-based learning opportunities conducted for over a decade with large enrollment classes of chemical (and since the fall 2015 semester) petroleum engineering freshmen.

A primary objective of the first-year experience in our School is to provide a solid foundation in basic engineering principles and applications associated with our degree programs through problem-based and project-based learning activities. The approach taken is a blending of directed problem-solving activities in a collaborative learning environment coupled with *Team Challenges* through which groups of four freshmen engineering students engage in actively constructing systems for solving practical engineering problems. This approach brings to students a vibrant, interactive approach to learning about chemical and petroleum engineering fundamentals at a time when individual anticipation (and anxiety) about studying engineering is perhaps at its highest.

Offered in a two-day per week format, course activities are structured to engage students in problem-solving strategies one day per week with the hands-on Team Challenges the second day each week. Significant course content and mentoring is provided outside of class in a "flipped-classroom" style.

By assembling and testing a variety of simple engineering systems, students learn about engineering applications of math and science principles. Examples of systems studied include the development of a centrifugal pump curve using a simple, inexpensive apparatus; investigating level-control for continuous flow into and out of a small tank using LEGO NXT™ controllers/sensors; evaluating performance of a double-pipe heat exchanger using Vernier™ meters and sensors; and assessing performance of a simple wind turbine as a function of changes in various parameters such as blade design, wind speed, etc. Individual students are provided an opportunity to quickly build relationships and skills for teamwork, leadership and collaboration along with gaining an understanding of designing experiments, collecting and analyzing data, and contextualizing the meaning of the work within a broader focus on the practice of engineering.

Student enrollment in the two semester course sequence has grown significantly over the years since its inception in 2006 from an enrollment between 30-40 students each semester to a high of 173 in the fall 2015 semester.

The evolution of the course and adaptations for large student enrollment is discussed.

Introduction

In 2009, the first survey of freshman chemical engineering courses was conducted by the AICHE Chemical Engineering Education Special Projects Committee. The first year experience for chemical engineering freshman has been shown to vary widely across a spectrum ranging from a common first year (among all engineering majors) with no chemical engineering-specific activities or topics to a discipline-specific, required chemical engineering course.[1] Foremost among the priorities given among the variety of course constructs were to provide students a framework within which they could better understand the nature of chemical engineering while enabling the development of a strong problem-solving skill set appropriate to the discipline.

Likewise, our course structure has evolved to achieve this desired outcome of familiarizing freshmen with the nature of chemical engineering practice while also building in students a problem-solving skill set appropriate to any engineering discipline (or, practically any STEM field).

An added factor driving the nature of our first year experience is the historically strong involvement our students have had in the co-operative education program through our university. Participation is not required, but approximately 65% of all chemical engineering Bachelors of Science graduates from our School (spanning 15+ years of data) participate in the university co-op program (not including the significant number of students which participate in industrial summer internships—not tracked by the university). Over 95% of B.S. graduates enter traditional industrial positions in regional industries.

In light of these facts and given the opportunity for our freshmen to participate in co-operative education and summer internship job interviews (with some securing jobs as early as the summer after the freshman year) the structure of this course have continuously evolved toward a strong engagement in activities characterized both as problem-based learning and project-based learning. To heighten the interest of student in engineering topics, the author has introduced a variety of projects which expose students to the broad topics of heat transfer, automatic process controls, reaction processes, etc. through which they can begin to relate their STEM fundamentals to practical applications. Figure 1 at right illustrates one student-designed project for pH control in tank with a continuous inflow and outflow of a dilute acid stream requiring neutralization.

Figure 1. Student designed pH control process

First-year course sequence

The latest incarnation of the two-course freshman sequence has been driven by regular feedback from students, upper-class mentors and employers (who often comment on the nature of student interviews with first and second year chemical engineering students). The revival of the petroleum engineering degree at our university and its inclusion within our School (and with several common courses in the early stages of that degree program) have also influenced, somewhat, the content of the courses.

The course sequence comprises a one-semester-credit hour fall term and a three-semester-credit hour spring term. For the fall 2016 semester, class meetings increased from once per week to twice weekly (again, as a result of constituent feedback). Spring term meetings continue at a frequency of twice weekly. In 2015, our college of engineering began funding a mentoring program for each engineering department—with the result that our course sequence is now provided with six upper-class mentors each term. These students assist with team activities both during the class period and outside of class and provide tutoring on a regular basis.

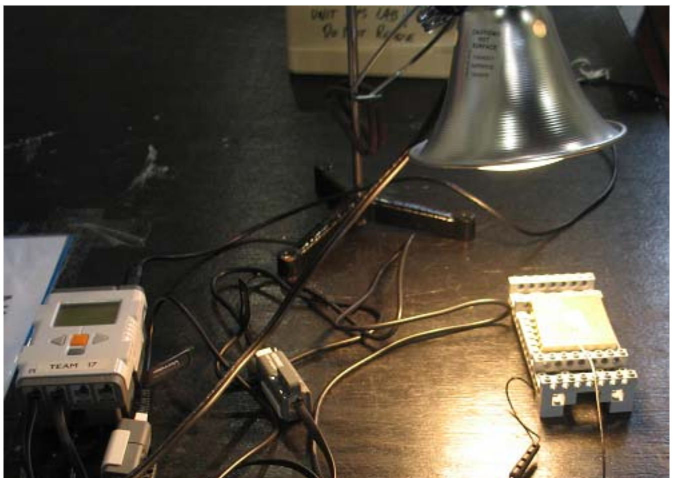

Figure 2. Study of heat transfer through metals

During one class period weekly, students practice problem solving techniques—engaging in collaborative learning with activities directed by one member of a two faculty member team. During the second weekly class meeting, students gather in self-selected teams for work on assigned projects—guided by the upper-class mentors and a faculty member.

Figure 2 illustrates a simple experiment for evaluating the steady-state rate of heat transfer through different metals.

Problem-based? Project-based? Flipped?

The efficacy of innovations in both pedagogical methodology and "tactical" approaches to classroom use has been well documented in the educational literature.

Problem-based learning has been characterized as:

- Engaging students in topically-relevant problems of a relatively narrow focus (in comparison to the "project-based learning" approach
- Students participating in problem definition and clarity through interactive discourse
- Solving problems iteratively and methodically as students construct a framework within which new learning occurs.

Such an approach involves students much more intimately in the process of learning than in traditional lecture methods through active engagement with peers, mentors and the instructor.[2]

Project-based learning may be described as:

- Involving more substantial projects (in comparison to problem-based learning) over an extended period of time
- Engaging students in a process of discovery with distinct phases of research, design, development and testing activities

- Requiring student self-assessment and the acquisition and/or use of a variety of skills over the project lifetime.

The flipped classroom has been described as any number of classroom environments whereby the traditional presentation of course content is "flipped" to an "outside of class" delivery with student involvement through self- and team-discovery activities directed during the class period. Such an approach has been increasingly popularized through all levels of education[3-6].

The literature reports both successes and challenges of each of these approaches depending upon a variety of factors including: strength of interactions with instructor and mentors[7], and the use of real-world projects and the balance of students' self-efficacy with regard to studying engineering, and student perceptions of learning versus grades[8-9].

We have blended each of these approaches in our first-year course sequence, refining semester-by-semester the approach to assess student responses—both in self-assessment for attaining learning objectives and in student performance in meeting course outcomes.

Current Course Structure

Following course assessment and evaluation for the 2014-15 academic year, student responses clearly indicated a desire to have more contact time in the fall term. The course was redesigned to span two class meetings weekly with one dedicated to problem-based learning, using *Elementary Principles of Chemical Processes* by Felder, Rousseau and Bullard (Wiley, ISBN-13: 978-0-470-61629-1) as our primary reference. The second class meeting each week is dedicated to a series of project-based learning exercises or *Team Challenges*. Continuing enrollment growth requires us to divide the class into three groups—each group pursuing a separate Team Challenge for a period of 2-3 weeks. Upon completion of a Team Challenge, each group rotates—finishing the three team challenges shortly before the end of the semester.

Team Formation

At the beginning of each semester students are allowed to self-select teams of four members each. Within teams, each member serves in a designated role (e.g. Team Leader, Data Recorder, Safety Officer, etc.)—rotation roles with each rotation to a new Team Challenge.

Among the desired outcomes for teams are:

1) Strengthening of working relationships among students—particularly for improving learning and performance during the problem-based class periods
2) Growth of "soft" skills including leadership combined with a sense of teamwork and service to others, project planning and management, and ethos of determination and intensity of effort and focus to achieve a goal
3) Practice of project completion from inception through experimentation, data collection and analysis and report writing and presentations.

Early in the fall term, it is fascinating to watch as students undergo stages of development as they transition from what most experience as a traditional lecture environment in high school to an entirely new structure within which they must learn to take ownership in the learning process. This growth phase can be somewhat "precarious" as many students suddenly realize that the process of becoming a practicing engineer is a rigorous, time-consuming endeavor. The intimate involvement of both instructors and mentors is absolutely essential during this phase to reassure students of their capabilities, to assuage worries about grading versus learning, and to encourage persistence. Thus the vital role of healthy-functioning teams is clearly evidenced in promoting student success.

Managing Large Enrollments

Our chemical engineering undergraduate enrollment has continued to grow unrelentingly from a low of 175 in 2005 to repeated historic records each of the past five years with a current enrollment of almost 450 undergraduates. This growth has expectedly been reflected in a surge in freshman enrollment (from 30-40 students in 2005) to an enrollment of 175 in the fall 2015 semester. As previously mentioned, this includes students (approximately 25) enrolling in the new petroleum engineering undergraduate degree program.

Accommodating such a large enrollment in a single section has required creative course design. Our auditorium allows all students to participate in the problem-based learning sessions while Team Challenges are conducted in various locations including the auditorium and our Unit Operations laboratory.

Team Challenges and Learning Outcomes

For the 2016-17 academic year, each semester comprised three team challenges through which all teams rotated over the course of the semester.

For the fall 2016 semester, the three Team Challenges were:

- Study of thermal conductivity through different metals
- Energy transfer and efficiency via a wind turbine
- Investigation of centrifugal pump performance and fluid flow

The Team Challenges for the spring 2017 semester are:

- Construction and performance of a double-pipe heat exchanger
- Performance and economics of a solar powered oven
- Design of an analog temperature indicator using LEGO NXT and Vernier sensor technology

Team Challenges that have been used in past semesters include:

- Tank level control
- pH control in a continuously-mixed tank
- Design of a processing station for handling silicon wafers

Each of these Team Challenges have common learning outcomes that have evolved over the eleven years that I have developed and taught the course.

Learning Outcomes common to all Team Challenges and to the problem-based learning activities are:

- Analyze fundamental chemical and petroleum engineering problems and systematically develop appropriate solutions
- Use basic Excel tools to collect and analyze data from your Team Challenges and use this process for making design and performance improvements
- Use the Engineering Design Cycle concept for approaching Team Challenges and for making design improvements
- Develop a technical problem from a word description through detailed definition using appropriate math, chemistry and physics principles, using drawings, symbols and appropriate models to reach a solution
- Explain to someone in your family (or a non-engineer) what chemical and petroleum engineering is about—giving practical examples.

Learning Outcomes associated with this course sequence are structured to follow guidelines provided by the ABET (Accreditation Board for Engineering and Technology) Student Outcomes. The flipped classroom environment used for this first year course sequence is ideally suited for students to begin developing the skills necessary for achieving these student outcomes.

Team Challenge Example—Investigation of centrifugal pump performance and fluid flow

The three figures shown below (extracted from the Team Challenge material provided to students outside of class) serve to illustrate the structure of the project-based activities. As has been strongly emphasized through the chemical process industries and through AICHE, developing a culture of safety among our future practicing engineers is incumbent on us as educators. We begin the emphasis on safety in our first semester and carry this through the curriculum in various courses including a dedicated course to Process Safety.

CHE 1101 Team Challenge

Investigation of centrifugal pump performance and fluid flow

SAFETY FIRST!

1) ALWAYS wear safety glasses when working in ANY lab (please replace in designated when finishing each session).

2) Water and electricity do not mix! To safeguard against shocking hazards, the switch activated outlet you have been provided (for on/off control of your submersible pump) has been equipped with a Ground Fault Circuit Interrupter (GFCI) outlet. DO NOT plug your submersible pump into anything other than the GFCI plug provided. It has been wired with a switch to allow convenient switching on/off of the submersible pump.

   You MUST be constantly aware of your surroundings and avoid accumulation of any water leaks in your workspace. Notify the Instructor of any persistent leaks in your apparatus.

3) Before starting the experiment, your SAFETY OFFICER must submit a completed (as appropriate) *Job Safety Analysis* form.

The successful report and PowerPoint presentation required for this Team Challenge will accomplish the objectives below

1) A carefully written background of centrifugal pumps is provided, citing references supporting your information. This must include how pumps are used in industry and must describe the different kinds of pumps and why centrifugal pumps are so commonly used in comparison to others.

2) Safety considerations are addressed, not only for your specific Team Challenge, but for the use of pumps in industry. What kinds of conditions might pose safety hazards?

3) Correct conversion of units measured in your experiment to proper ENGLISH UNITS representing power delivered by the

By providing students a step-by-step guide, supplemented with mentoring by upper-class students and instructor assistance, even a significant number of student teams (34 for the fall 2016 semester) are able to work independently with a high probability of success with minimal correction or interference.

4) Proper assembly of the experimental apparatus and preliminary testing ensures correct operation. Details are provided in this handout, but one example of incorrect operation would be that the pump is too powerful for the tubing system and actually forces water out of the vertical tube attached to the PVC pipe (used as a manometer). In this case, you would slightly close the green/blue valve placed at the pump exit to lower the pressure and flow rate of the pump preventing it from overflowing the manometer.

Fig. 1 Equipment configuration inside the bucket

5) Ample data points (10+) are taken at different discharge point elevations, measuring discharge flow rate and elevation of water in the manometer (at EACH discharge point). Also, you should repeat the measurements for four data sets (adjusting the discharge point from low to high settings, from high back to low settings then repeating this cycle). This will give you four data sets for comparing statistically, using the Analysis of Variance (ANOVA) method in Excel. This method allows your to check multiple data sets for statistical consistency. ANOVA is discussed in more detail later in this handout.

6) Plotting ALL data (both raw experimental measurements AND calculated measurements) in a variety of graphical forms using Excel to demonstrate both your knowledge of graphing techniques in Excel and your ability to gain understanding of the relationships between power, flow rate and pressure (demonstrated by converting the water elevation in the manometer to appropriate pressure units).

7) Discussing all points described below in your report

8) Preparing a PowerPoint presentation with 8-10 slides (minimum) with "clean" background (avoid goofy graphics and bold colors which distract from the true content of your slides—this is a common mistake among underclassmen and is unprofessional in a technical presentation). Keep slides simple (avoid too many words). Use bulleted items and labeled pictures. You ARE allowed to cut and paste my pictures into your PowerPoint slides and report as long as your use correct labeling.

Equipment & Process Details

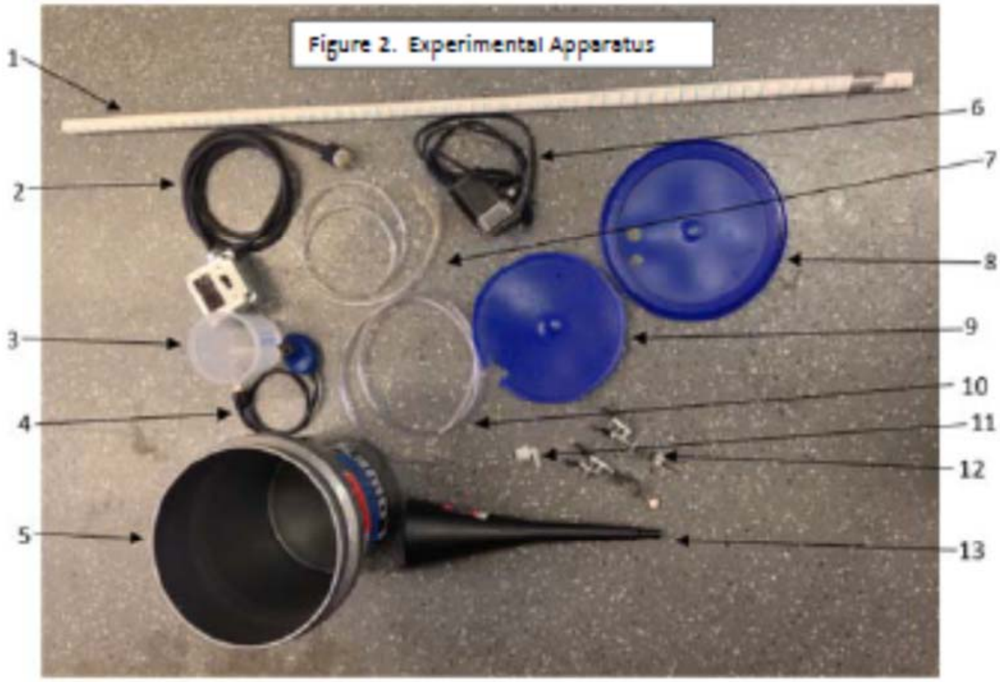

Figure 2. Experimental Apparatus

1. Measuring pipe	5. 5-gallon bucket	9. Bucket insert	13. Funnel
2. Two-gang apparatus	6. Water pump	10. Tube 2 (larger)	
3. 1000ml beaker	7. Tube 1 (smaller)	11. Tube 2 nozzle insert	
4. Load tester	8. Bucket cap	12. Stand clamp (2)	

From the picture above you can see that your available equipment consists of

- a submersible pump—item 6 in the Figure 2 above, the discharge of water from the pump occurs at the top of the pump (see Figure 1). A short length of 3/8" ID tubing is attached directly to the pump. A polyethylene tee is then used to attach two sections of 3/8" ID tubing (items 7 and 10 in the Figure 2)—EACH approximately five feet in length. A valve has been inserted at the pump discharge. This valve is normally left completely open. If, however, you notice your specific pump discharging water from the top of the manometer, you will need to close it slightly so that the manometer doesn't overflow. **Once you make this adjustment DO NOT change the valve setting throughout your experiment.**

Observations and Conclusions

Continued enrollment growth and the inclusion of the new petroleum engineering majors has influenced and shaped the changes to our freshman year course sequence.

The introduction of a problem-based/project-based learning approach and restructuring the first year experience after the model of a flipped classroom environment has been met with strong and enthusiastic support from all constituent groups (students, faculty, advisory board members and industry representatives).

Each year, our External Advisory Board reviews the freshmen Team Challenges via a poster symposium near the end of the spring semester. Reviews remain strong among board members regarding the influence this course sequence has on the preparation of our students for the advancing difficulty of the chemical and petroleum engineering curriculum and on their preparation for the work environment.

Anecdotally, industry representatives have positively noted the added preparation this course sequence (particularly the effects of the Team Challenges) has had on student interviews. Experience gained in this first year experience has given many students a framework for engineering concepts and principles (with chemical and petroleum engineering applications) that they would otherwise not get until much later in the curriculum. As one student noted, "[the course] began at a fast pace, but concepts were explained in depth…great way of teaching students how to think and break down problem".

At the time of this writing, one student (a current freshman) reported enthusiastically, "Hey dock, I just got a co-op job!" When asked what he attributed to the success, he said, "They specifically told me it was the project work I had done in this class!"

Formal course assessment includes regular evaluations of individual student performance, faculty and mentor evaluations of Team Challenge reports, periodic surveys of students regarding their perceived growth and understanding, an end-of-semester "faculty evaluation" survey includes as part of the Instructor Course Assessment.

Table 1 shows student ratings for two general assessment questions included in faculty evaluations at the conclusion of each course. These questions are part of a set of questions required by university assessment. The generality of the questions and the evolving nature of the first-year course sequence prevent quantitative comparisons of the data. The continuing growth in enrollment has posed challenges for us, yet, a generally positive trend is clear from the earliest stages of this course offering.

Table 1. Sample ratings from the faculty evaluation survey

Year	**"I learned a great deal in this class".** Rating* (out of 5)/No students	**"The Presentation of Course Content helped me learn in this class"**
2016	4.3/102	4.0/102
2015	4.0/85	3.8/85
2014	4.3/50	4.0/50
2013	4.5/71	4.2/71
2012	4.5/55	3.9/55

2011	4.5/34	4.4/34
2010	4.3/53	4.3/53
2009	4.3/35	4.2/35
2008	4.0/51	4.0/51
2007	3.6/19	4.0/19
2006**	NA	NA
2005**	3.19/30	3.79/30

*The rating is conducted on a five point scale—1=Strongly Disagree, 5=Strongly Agree
**Survey questions in '05 & '06 were worded somewhat differently.

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