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Problem-Based Learning: A Tale of Three Courses

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Abstract

Courses in engineering and science are typically taught deductively, through transmission of information from instructor to student, followed by practice problems to reinforce what was covered in readings and lectures. Yet in our personal and professional lives, we learn experientially – by facing a real situation and attempting to address it, and from our related successes and failures.

Experiential education emphasizes a mixture of content and experiences, connection of learning to meaning and to the world outside of the classroom, and reflection on this for higher order learning and development of new skills and capabilities. Problem-based Learning (PBL) is an inductive, active learning approach that connects learning to real world problems, and provides a context in which students can tether their knowledge and internalize course concepts. Students are thus motivated to seek out a deeper understanding of the concepts they need to address the problems presented in a course.

This research focuses on going beyond the technical lecture to enhance the student experience through PBL and experiential education techniques, based on implementation in the Rochester Institute of Technology's (RIT) College of Engineering Technology, in courses in telecommunications engineering and environmental sustainability. PBL content was developed and implemented with a goal of motivating and exciting students, and enabling them to internalize the knowledge for deeper understanding. This included enhancing students' ability to think critically about real-world challenges in engineering and sustainability, as well as their ability to address these challenges through an inductive, experiential approach that mirrors the way they will need to approach problem solving in professional practice.

Assessments suggest initial challenges for students in self-directed research and working outside of their comfort zone, but ultimately there is evidence of tangible value for student learning, skill development, and ability to succeed and thrive in the field.

Keywords: engineering education, experiential education, problem-based learning

Introduction

In recent years, the ability of engineering programs to attract and retain students and the preparation of engineering faculty as engineering educators have come under scrutiny.

Fear that the United States may lag behind the engineering and innovation curve, as other nations enhance their technological capabilities, has led to numerous calls to improve engineering education (Sheppard, Macatangay, Colby, & Sullivan, 2008). Additionally, extensive research has warned that the combination of a predicted demand for engineers and changing demographics in the United States point to the need for revolutionary changes in the preparation of engineers (Jamieson & Lohmann, 2012; McGee & Bentley, 2017; National Science Foundation, 2014). Engineering education researchers have argued the educational benefits of deductive or student centered learning strategies (Felder, Brent, & Prince, 2011; Prince & Felder, 2006). In this paper, we describe one college's attempts to enhance faculty preparation and pedagogical practices with the goals of improving student engagement and promoting deeper learning. We offer three specific examples of alternative teaching strategies as evidence for those who wish to consider moving away from the traditional technical lecture.

Problem-Based Learning in Engineering Education

Historically, engineering faculty have been hired, rewarded, and promoted based on demonstrated expertise in their fields. However, these faculty generally lack background in educational theory and have had no significant pedagogical training (Froyd & Lohmann, 2014). Engineering education researchers have even labeled engineering faculty "Unprepared Practitioners of a Highly Skilled Profession" (Felder et al., 2011, p. 89). Like our predecessors who taught us, engineering faculty members have adopted the teaching strategies we learned as students (Lortie, 1975). Although some researchers have identified attempts to make engineering programs more engaging (Jamieson & Lohmann, 2012), others have argued that engineering programs still limit students' exposure to real world problems and overemphasize "decontextualized problem-solving", benefitting only "… those students who are younger versions of the professors themselves" (Christman, 2017). The primary mode of instruction in engineering has been focused on a "banking method" of information transmission (Freire, 1970) focused on the presentation of facts through lecture. Despite extensive research that has demonstrated their ineffectiveness, (Felder, 2012; Prince & Felder, 2006), lectures have "… dominated engineering education since its inception…" (Felder, 2012, p. 9).

On the student side of the equation, decades of research indicate that retention continues to be a challenge for engineering education (Goodman, Cunningham, & Lachapelle, 2002; Jamieson & Lohmann, 2012; Seymour & Hewitt, 1997; Tonso, 2006), and discussions of student retention remain prominent on college campuses today. To increase student persistence and attract a larger and more diverse student body, researcher have argued the need to "… make our engineering programs more engaging, relevant, and welcoming" (Jamieson & Lohmann, 2012, p. 21). Problem-based learning (PBL) is an instructional technique that situates ill-defined problems at the focal point of student learning and offers the promise of enhanced student engagement. Advocates of PBL tout numerous benefits, including enhanced problem-solving skills, deeper learning, enhanced knowledge transfer and retention, and increased motivation (Maskell, 1999; Matthew & Hughes, 1994; Prince & Felder, 2006; Savin-Baden & Howell, 2004).

In PBL, the problem or scenario provided to the students serves to activate learning, while the challenge of finding a solution drives the learning process (Savin-Baden, 2008). Students are accountable for their own self-directed learning in an active, constructivist manner while working in small teams seeking a common goal. In their analysis of PBL problem creation, Jonassen & Hung (2008) presented a rigorous review of problem categorizations ranging from well-structured through ill-defined, and described the relationship between structure and complexity in successful PBL implementations. They argued that good PBL problems should be (a) open-ended and ill-defined; (b) of challenging complexity, engaging, and adapted to prior learning of students; and (c) realistic.

Pedagogical introduction of problem-based learning is credited to the medical community (Savin-Baden & Howell, 2004), and has been recognized for "inducing revolutionary undergraduate medical reform" (Maudsley, (1999). With a seemingly parallel objective over a multi-year period, the National Science Foundation has continued to appeal to researchers to revolutionize engineering education (National Science Foundation, 2014, 2018).

As PBL has become more widespread, several changes have taken place. Early PBL was tightly structured with few implementation alternatives. More recently, the notion of problem based learning has become "… diverse, complex and contested" (Savin-Baden, 2008, p. 101). Researchers acknowledge that PBL is not a panacea for all teaching and learning environments (Jonassen & Hung, 2008), and educators face new challenges when deciding to delve into PBL techniques. Potential concerns include vague learning expectations or outcomes, changes in teaching and learning approach (Maudsley, 1999), and requirements for "instantaneous changes in curriculum, instruction, and assessment practices…" (Barron et al., 1998, p. 271).

Engineering educators face many challenges and potential pitfalls associated with course content, teaching and learning tools, and pedagogical approaches. Often, these challenges come in the form of expectations placed on the instructor from accrediting bodies, students and their family members, industry colleagues, or employers of graduates. With these understandings, engineering educators may be inclined to adopt technology or teaching tools for marketing rather than educational reasons. Of additional concern is the culture of engineering education, which has historically been supportive of a highly empirical approach to teaching and learning. Engineering educators do not approach education innovation in the same way they would approach engineering innovation. Instead of basing educational changes on extant research and established learning theories, faculty implement changes based on their own personal experiences in the classroom as students or teachers (Jamieson & Lohmann, 2012). Undesirable results are a predictable outcome of these siloed approaches.

In an effort to promote meaningful pedagogical change and increase the capabilities of faculty, the dean of RIT's College of Engineering Technology funded a multi-day PBL workshop taught by a nationally recognized engineering educator, and provided course development funds to faculty participants willing to move away from lecture and redesign courses in a PBL format. In the following sections, we share the experiences and preliminary educational results from three faculty members who have thus modified their teaching practices by incorporating evidenced-based teaching strategies for PBL in their classrooms. For each case, we present a description of the course under investigation, how the instructor implemented PBL strategies, how each specific problem supported student learning, and a preliminary assessment of the learning environment and results obtained.

Course 1: Graduate Network Engineering

Principles of Telecommunications Network Engineering is an elective course in the Master of Science in Telecommunications program at RIT. The focus of this course is to design and test data networks via simulation and physical implementation. Routing protocols and Quality of Service (QoS) are covered with respect to redundancy and Service Level Agreements

(SLAs). The course covers network design principles and methodologies as they apply to circuit, packet switched, and synchronization networks. Course topics include traffic engineering models, queuing theory, timing and synchronization, design of voice and data networks, and IP routing protocols. Students configure router and switch topologies in both virtual and physical environments.

The course learning outcomes are defined as:

1. Determine maximum allowable slip rate, jitter and wander based on CCITT, ANSI and IEEE standards,
2. Detect and resolve timing loops in timing distribution networks, and
3. Assess various topologies and protocols for particular network services, applications and levels of security.

This research project is focused on a PBL approach to learning outcome 3.

The Scenario

The fall semester of 2018 presented an opportunity to rebuild our instructional laboratory for telecommunications systems following a renovation of that space. Students were asked to inventory, install and bring on-line the remaining equipment following the renovation. This required mounting hardware, making cables and re-establishing communication with all equipment – routers, switches, servers, IP phones and various other devices required to create networks to implement networking protocols.

The Problem/Framework

The problem statement created an environment for students to learn essential principles and skills required of networking professionals by mirroring the engineering environment within our laboratory. The "problem" was not only to bring a laboratory online based on a set of requirements, but to coordinate and communicate with other groups. The instructor introduced the problem and requirements, and made clear the budget limitations and the extent of department monetary assistance in procuring miscellaneous items such as cables, connectors and hand tools. This supported the course outcomes as students needed to configure and implement the equipment and systems to perform the lab exercises in support of the lecture material. The capabilities must be engineered and tested to ensure proper operation of the systems and a student experience that is instructionally tied to the learning outcomes of the course. Specified requirements for the laboratory are summarized in Table 1.

Table 1: Requirements -Telecommunications Systems Laboratory Rebuild

Requirements of the Lab	Requirements of the Lab to Support Course Syllabus	Other Features/Capabilities
- Internet access via campus - Rack mounted – AC powered routing and switching equipment - A proprietary soft switch platform - VoIP phones with proper IOS loads - Console interface command line access	- A suite of laboratory concepts including VLANS, MPLS, BGP, IGPs (RIP, OSPF, EIGRP), ACLs, DHCP, VPNs and NAT	- Sufficient campus data jacks - Required computer software loads and operating systems - Computer configurations and capabilities - VMware selection - Network simulation software-selection/ installation - Sufficient and proper Interface cables for console interface router to router, and router to switch connections

Class Organization

The class was organized into three groups of seven students. Each group selected a liaison to interface with the other group liaisons to coordinate activity and log progress. This was needed to coordinate the individual contributions of each group toward the completion of a fully functional laboratory environment. As each group progressed it was imperative that the next group be aware of what had been accomplished, and any issues that needed to be addressed before moving forward. Students were required to make use of what was present with only limited access to additional materials.

Students created laboratory reports detailing the configuration and testing procedures to assess various topologies and protocols for particular network services, applications and levels of security to support the course objectives. The reports of one group were given to another group for review. Each group was asked to read and critique the reports and perform the configuration and testing procedures contained in each report. During the final two weeks of the semester, each student was required to perform a lab practical exam. The instructor observed that students had a greater facility working with the equipment and a greater level of comfort applying concepts related to various topologies and protocols for particular network services, applications, and levels of security than students in previous semesters. Initial observations seem to indicate that students had a more holistic, deeper, and practical understanding of these concepts in the PBL classroom.

Assessment

The three liaisons met with the instructor weekly to discuss and evaluate progress – successes, difficulties, individual group member performance, and next steps. A checklist was used to account for completed, pending, and problem items. Near the end of the semester the student groups were required to demonstrate the laboratory exercises and explain the procedures and documentation created. Each laboratory document contained a list of learning objectives and an appendix to detail how a given set of procedures for each lab mapped to the learning objectives for the course. The instructor reviewed and rated each laboratory for effectiveness in accomplishing the required objectives. The assessment elements are summarized in Table 2.

Table 2: Assessment Elements – Telecommunications Laboratory Rebuild

Equipment	**Laboratory exercises**
- Equipment functionality - Equipment accessibility	- Procedural clarity - Diagrammatic clarity - Inclusion of course objectives - Reflective and analytical questions

Discussion

It was clear that students took ownership of the process and saw this as an opportunity to create an experience for future students. It created excitement as the process was interactive and allowed for creativity and information gathering, testing, and evaluation of various topologies required to support the course learning outcomes. In talking with the students regarding the concepts, it was clear that each student had a deeper understanding of the specific elements of the networking principles covered in the class and supported by the laboratory exercises they developed.

The PBL approach afforded the instructor the opportunity to embrace student-centered teaching strategies to accomplish the course objectives and support learning outcomes and in some ways become a peer contributor to the process. The instructor and students became co-developers and a unique relationship was forged, providing an opportunity not previously experienced by the students. All hailed from the Indian subcontinent where a hierarchal social and educational system exits, in which collaboration with professors is uncommon. This allowed students to openly communicate and develop confidence in sharing their knowledge and insights into how they could more easily learn these concepts.

As with any group activity, one challenge is to ensure member engagement. It was clear that in two of the groups, some members were not completely involved in the initial stages. This was due to lack of confidence and or unfamiliarity with this environment. Once this was overcome by small successes, these students became more engaged and contributed to the completion of the laboratory design. This experience allowed the instructor to be more involved with the students and establish a relationship of trust, which in turn allowed the students to feel more comfortable with the instructor and their place in a new educational system.

Course 2: Graduate Wireless Communications

For the past few years, our program has adopted the use of software-defined radios (SDR) in wireless communications courses, both at undergraduate and graduate levels. These have been used to illustrate fundamental concepts such as filtering, sampling, modulation, pulse shaping and synchronization.

At the undergraduate level, students have been asked to solve relatively complex problems using the radios. Among them are the implementation of an amplitude-modulated analog radio, a Morse-code on-off keying (OOK) wireless telegraph system, and a binary phase-shift keying (BPSK) transceiver. The most successful student-led project in terms of student learning and motivation has been the capture and processing of weather images produced by the National Oceanic and Aeronautics Administration (NOAA) satellites (Bazdresch, Velayudhan

& Johnson, 2016; Velayudhan & Bazdresch, 2016). These activities have increased students' motivation, and have resulted in deeper and more meaningful learning.

It has been long recognized that courses based on SDR can be highly integrative for curricula in electrical engineering undergraduate education (Bilen et al., 2014), and several different approaches exist (Xu, Kui, Hei & Chang, 2017; Bazdresch, 2011), (Gunther & Moon, 2013). However, there are fewer proposals for graduate education (Petrova, Achtzehn & Mähönen, 2014), and even fewer specifically for telecommunications engineering technology.

A PBL approach using SDR in a graduate program is subject to several constraints. Graduate students taking the course may have either an electrical or a computer engineering background. Although some students may have several years of experience in the telecom industry, they may have forgotten some of the theoretical underpinnings of their educational preparation. They have a broad range of interests, and may desire to focus not on the minutiae of physical-layer wireless communications but on fiber, networking, programming, or even the business side of the telecom industry.

At the same time, teaching using SDR poses some difficult challenges (Bazdresch, 2016), such as the complexity of the existing software packages, and the need for students to grasp a large number of ideas before even the simplest experiments can be performed in a meaningful way. In addition, a graduate course is typically required to include more advanced and rigorous mathematical analysis, which makes it more difficult to justify activities that take students away from their textbooks. Nevertheless, our experience shows that the learning benefits are worth the effort. In the following paragraphs we describe our current approach and our ongoing efforts to improve the efficacy of the proposed activities using research-based PBL techniques.

The learning outcomes for this graduate course are described as:

1. Model and predict the capacity of the Rayleigh fading channel.
2. Model, simulate, implement and evaluate the performance of a digital communications system over the wireless channel.
3. Design, simulate and evaluate communications systems that use coding, spatial diversity, and transmit diversity.
4. Design, simulate and evaluate systems that use space-time coding.

This research project is focused on a PBL approach to learning outcome 2, specifically regarding system implementation.

Current approach

The course devotes six class sessions (a total of nine hours) to lab work. After students solve a few relatively simple problems using SDR, they become acquainted with the tools and the hardware, and they gain a level of proficiency in the fundamental concepts such as sampling, spectrum up- and down-conversion, and performance evaluation.

The majority of their learning occurs with a more complex problem, which requires transmission and reception of a quadrature phase-shift keying signal (QPSK). Students implement their solution by integrating several available functional blocks, such as channel estimators, and frequency and symbol synchronizers. Their main task is to obtain an "open" constellation in the receiver. While the operative challenge is to select the right functional blocks and to connect them in the right order, their real cognitive challenge occurs when they are asked to (a) prove that their system is operational and quantify their performance, and (b) explain and justify their block selection, and why each particular block is necessary.

Students are assessed by the efficiency of their design, the performance obtained, and their ability to explain each block's function and operation, as well as the overall understanding of the entire system. The assessment is both quantitative, for example, by comparing the mean square error of their system to an ideal one, and qualitative, by ranking their level of comprehension by the rigor, correctness and clarity of their explanations. Over the past few years, this approach has demonstrated substantial learning benefits compared to a traditional, pure lecture course; however, we believe that our approach can still be improved.

Improved PBL approach

Currently, students select pre-existing blocks from a large library, configure them and interconnect them to solve a problem. While their solution must be correct and they have to explain and justify their choices, the use of pre-existing building blocks means that students are not yet learning as actively as they could. Since PBL research indicates that student engagement and learning are correlated with the depth of their involvement in the solution, we propose an improved approach where students design and implement at least some of their system's functional blocks. These changes are a result of a curricular redesign and prompted by the PBL workshop mentioned in this paper's introduction.

There are two main challenges in this endeavor. One is that in SDR applications, implementation means programming, a skill that has proven difficult for a large portion of our students. We intend to ameliorate this problem by having a concurrent bridge programming course. The second is that more active problem solving involves a rearrangement of the remaining lecture sessions that cover the remaining learning outcomes.

We propose to take an incremental approach, **and start by asking students to implement only one of their system's functional blocks from scratch**. In this way, we will be able to measure the effect on student learning and slowly readjust the rest of the course. Over time, students will take responsibility for larger portions of their designs.

Student's assessment will be supplemented by an evaluation of their ability not only to explain and to use a signal processing algorithm (which is what the functional blocks are), **but also to implement it in a computer language and simulate, test, debug, and evaluate it.** These activities clearly present a larger cognitive challenge, which we believe will translate to deeper learning.

Course 3: Undergraduate Environmental Sustainability Health and Safety Seminar

The Environmental Sustainability Health and Safety (ESHS) Seminar course provides first year students with a foundational understanding of ESHS issues in society and in the workplace, and expands their capabilities in critical thinking. First year students typically have little to no experience with practical applications of ESHS on which to ground the concepts we cover in class. Based on assessment in previous semesters, students don't always demonstrate internalization of the major concepts embedded in the course, and have difficulty grasping how the private sector can interact in society regarding ESHS issues. This research project was focused on applying PBL to address this gap in connection with course learning outcomes, which, among others, included the following:

1. Define & differentiate among environmental sustainability, health, and safety concepts.
2. Understand the importance of ESHS management in the workplace and in society.

Additional student learning objectives associated with the PBL project itself included functioning in teams, applying knowledge of contemporary issues in ESHS to identify and solve applied science problems, understanding the impact of solutions in a global and societal context, and effective communication.

The Problem/Framework

A PBL project was incorporated in the fall semester of 2018 as a means to give students an opportunity to engage more strongly in their own learning process, apply critical thinking skills to a real-world problem, and put the concepts into practice in a specific context. The overarching "problem" was based on global challenges for sustainable development, and the need for action worldwide from businesses as well as governments and individuals to balance economic growth with social inclusion and environmental protection (United Nations, 2018). The project required students to develop and propose a strategy for a specific multinational firm to support achievement of an appropriate sustainable development goal (SDG), based on the Global Goals for Sustainable Development established by the United Nations in 2015. Students had to identify a firm on which to base their project, and then determine which of the 17 goals would be most relevant and appropriate for their firm to support, based on its context. This was intentionally open-ended, and could include, for example, the firm's environmental, social, and economic impacts, sphere of influence, stakeholder interests, and how the firm could affect or be affected by the issue(s) related to each goal.

Students worked in small teams to identify and contextualize the problem associated with the selected goal, and then to develop a set of proposed objectives, targets, and actions for the firm to contribute to the global goal over the next five years, and present the approach to "top management" for the firm. For example, one team developed a proposal for Exxon

Mobil to contribute to SDG 7: Affordable and Clean Energy, with a strategy aimed at intensifying research and development of lower-emission energy solutions and investing in clean and renewable energy sources and technologies.

The project was introduced mid-semester to allow time for students to develop some degree of domain knowledge and critical thinking skills through class sessions and exercises, as well as field trips to industrial organizations. The assignment was structured in three parts: defining the problem, exploring the problem, and formulating a solution. The hierarchical assignment structure included questions as prompts to guide students toward the types of information needed to address the assignment. Class time was set aside for working on the project, and teams reported out in class on preliminary findings and challenges for each part of the assignment. The instructor also provided constructive feedback to give students the opportunity to address misconceptions or areas that merited further depth and improve on their work for the final proposal.

Assessment

Project assessment was based on completion of required components for defining and exploring the problem, formulating a solution, and presenting their proposal, according to an assignment rubric. The assessment criteria are summarized in Table 3.

Table 3: Assessment Criteria – Industry Contribution to UN Sustainable Development Goals

Background & Proposal Content	Format & Presentation
- Justification for SDG selection, including relevance for the firm - Targets and metrics associated with the SDG - Identification of stakeholders and opportunities for partnering	- Professional report including executive summary, background, proposal, and references - Effective communication and compelling argument - Meaningful contribution and engagement in the presentation

- Proposed industry actions and responsibilities to support the targets associated with the SDG - How progress and performance will be evaluated	

Eighty-six percent of students who completed the project achieved a grade of 85% or higher on the final proposal. Other elements of assessment included a sustainability knowledge assessment "quiz" given before and after the project, and feedback provided on the course evaluation. The sustainability knowledge assessment indicated a modest improvement in sustainability knowledge after completing the project. This is encouraging, however, the PBL content cannot be isolated as the driver for this improvement. Course evaluation ratings and comments suggested that students appreciated clear communication on the project, helpful feedback, support of student progress, and time in class to work on the assignment with access to the instructor. Suggestions for improvement included introducing the project earlier to spread out the due dates and allow more time to address feedback on previous parts or drafts.

Discussion

The PBL assignment was essentially a situated case/policy problem, according to Jonassen's typology (Jonassen & Hung, 2008), which involved a moderately structured, but open-ended, realistic problem with multiple reasoning paths and solutions. The level of complexity was moderate, but challenging for students based on the early point in their academic career, limited exposure to environmental management in an industrial context, and limited exposure to inductive learning.

Early in the semester, students struggled with seeking information and conducting independent research to support their project. However, most adapted quickly and were successful when given feedback to apply toward the next part of the assignment. The majority of the students seemed to fully engage with the open-ended nature of the PBL framework, and the two students who did not achieve above an 85% had encountered personal issues during the semester, which seemed to negatively impact their level of engagement. The team aspect and use of class time to communicate about and work on the project, as well as the realistic nature of the project helped to keep students interested and involved. Overall, the PBL project added value to the course, and feedback from students and instructor insights from the experience will enable continual improvement for future implementation of PBL.

Conclusions

In the preceding sections, we outlined three implementations of research-based, alternative teaching strategies conducted by faculty members with little or no prior experiences with formal PBL. In two cases, faculty members revised an existing course that they had previously delivered through traditional lecture. Based on assessments of the revised version of each course, we have provided anecdotal and to some extent quantitative evidence to demonstrate learning gains with the new teaching strategies. In both instances, an increase in student engagement and a greater sense of student-directed learning were evident.

In the other instance, as described in Course 2, the faculty member had included PBL activities in an undergraduate course for a period of several years and is now embarking on an effort to make significant improvements to his PBL approach for graduate students. Having gained an appreciation for the effectiveness of alternative teaching strategies at the undergraduate level, the graduate level implementation shows considerable promise.

In each of the three cases, faculty members challenged themselves to leave the comfort of traditional lecture for the potential of improved student learning. Guided by education research and wary of possible challenges associated with alternative teaching strategies, we have embraced PBL as a potential strategy to enhance student learning. While more research on PBL in engineering classrooms is needed, the efforts described here should encourage others to seek evidence-based teaching approaches to improve their own courses. As a team of researchers who believe in and are committed to the benefits of alternative teaching strategies, we encourage other engineering educators to immerse themselves in the extant education research. Because of a growing awareness of evidence-based educational methods, RIT is building momentum in the creation of engaging learning opportunities. Looking forward, we intend to build upon these early efforts and establish more formal research methodologies to engage in further study of PBL implementations in engineering classrooms.

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