Lessons Learned from Incorporating Problem-Based Learning and Lego System in Engineering Measurements Laboratory

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Abstract

As one of the most important developments in contemporary higher education, Problem-Based Learning (PBL) is widely used in most medical schools and is being proliferated in several other disciplines. A limited number of engineering educators have reported using PBL methods in their classes. However no literature in the field reports how to implement PBL, to what extent PBL should be implemented, the possible pitfalls in the implementation of PBL, and the design of problems using Lego System in an Engineering Measurements course.

This paper gives a brief introduction to PBL and describes assessment comparisons among three different types of instructional methods. The three methods are: 1) fully traditional content-based learning, 2) a combination of lecture-type instruction and PBL instruction, and 3) full PBL instructional methodology with a partial use of Lego RCX System. The assessment results indicated that, without compromising students' exam performance, the PBL method (when used partially or fully) significantly improved important skills in analyzing and solving open-ended, real-world problems, working cooperatively in teams, and communicating effectively, verbally and in writing.

The Lego RCX System demonstrated its superiority as an ideal platform in designing real-life problems in measurement and control, in controlling the problem difficulties, and in inspiring students' interest in class. However, we cannot take PBL as a panacea to cure all of the current engineering educational problems. Based on input from industrial representatives and experienced educators, student background, and student feedback in classes, we have provided suggestions on how to and how much one should implement PBL.

The major suggestions include balancing our engineering curriculum regarding the courses taught in traditional vs. PBL method, developing a balance within a PBL course, balancing the depth vs. breadth of class topics, fine tuning the process of transition from a traditional lecture-type class format to a PBL format by considering the students' specific background and personal characteristics, controlling the group size for effective communication and ease of scheduling, and employing the Cooperative Learning (CL) method to assure all group members are accountable for doing their share of the work and mastering all of the material to be learned. The implementation and assessment methods in this paper could serve as a prototype for other engineering courses using PBL. More problems using Lego RCX could be designed to form a PBL problem database for future reference in engineering measurement and control courses on the basis of our initial results.

Introduction

Several reports indicate that there is a need for change in undergraduate education.[1-4] The educators calling for change bemoan the lack of relevancy in many traditional courses and recommend eliminating the "plug–and–chug" cookbook approach to education. The Boyer Commission's report from the Carnegie Foundation,[5] "Reinventing Undergraduate Education: A Blueprint for American's Research Universities," provides an academic bill of rights for students. It includes (1) providing opportunities to learn through inquiry rather than simple transmission of knowledge, (2) training in the skills necessary for oral and written communication, and (3) preparing students carefully and comprehensively for whatever may lie beyond graduation.

A driving force behind this change is the realization that successful employment and citizenship at the present time require different knowledge and skills than in the past.[1, 6] Hence, in addition to instructors' more traditional role as providers of discipline-specific knowledge, they are being urged to adopt teaching strategies that help students to develop competencies identified as necessary for success:

- To analyze and solve open-ended, real-world problem
- To find, evaluate, and use appropriate learning resources,
- To work cooperatively in teams, and
- To communicate effectively, verbally and in writing.

Many of the reports mentioned earlier suggest several strategies to develop these skills. One of the most common strategies recommended is to use the problem-based learning (PBL) method of instruction.

Problem-Based Learning (PBL)

PBL had its beginning in the medical program at McMaster University in Hamilton, Ontario, Canada. Later, it was implemented in the medical programs at Michigan State and Harvard Universities. Currently, most medical schools are using the PBL method of instruction, and its use has proliferated in some other disciplines.[7] A limited number of engineering educators have reported using PBL methods in their classes.[8-11] However no literature in the field reports how to implement PBL, to what extent PBL should be implemented, the possible pitfalls in the implementation of PBL, and the design of problems using Lego System in an Engineering Measurements course.

In PBL, entire courses and individual topics within courses are introduced with complex open-ended focus problems whose solutions will require the knowledge and skills set forth in the course learning objectives.[12-15] Compared with the students taught conventionally, students taught using PBL acquire greater mastery of problem-solving, interpersonal, and life-long learning skills and are more likely to adopt a deep (as opposed to surface) approach to learning.[9, 15] Problem-based learning (PBL) can easily be adapted to address all requirements of ABET Engineering Criteria 3.[16] A comparison of a PBL method and the traditional approaches is given in Figure 1.

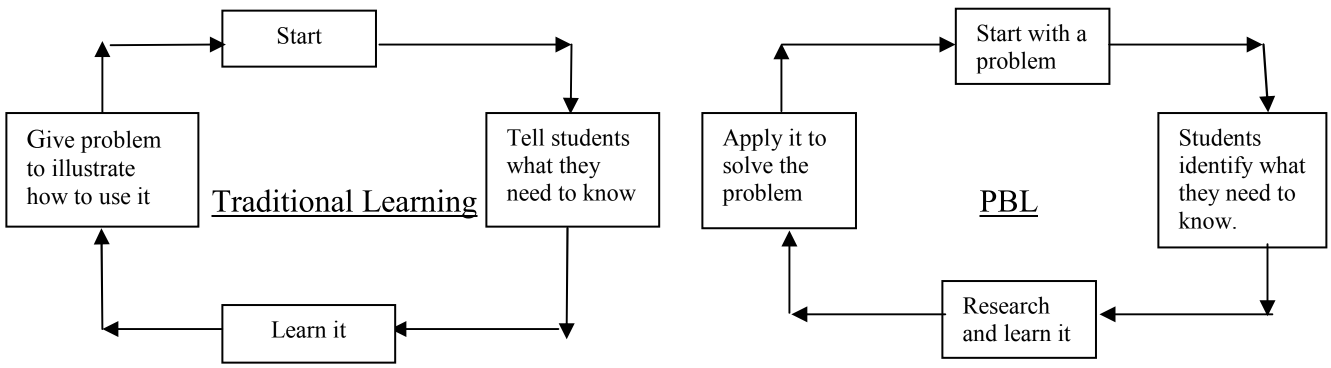

Fig. 1 Traditional vs Problem-Based Learning Processes

Both teacher and student roles change quite significantly from a speaker vs audience in a traditional mode of instruction to a director vs actor in PBL. The teacher must act as a coach and facilitator for students as they go about finding the solution to a problem. The student must transit from an audience to a knowledge explorer or active actor/actress while fully engaging in the learning process. Expected outcomes of using PBL are listed in Table 1.

Table 1. Expected Outcomes When Using PBL

1.	Since learning occurs in an environment similar to that in which the students will work, the problem-solving skills they learn will be more easily transferable to that work environment.
2.	Students no longer learn facts, skills, and concepts as separate entities, but instead see how they can be interconnected to solve real problems.
3.	Students learn to find, evaluate, and use appropriate learning resources.
4.	Students enhance their skill to work in teams.
5.	Students increase their communication skills by explaining the results of their independent research to team members and presenting a final report.

Method and Assessment

Engineering Measurements is a required course in the Mechanical Engineering (ME) curriculum at North Dakota State University, like in many ME curriculums at other universities. It consists of two 50-minute recitations and one two-hour laboratory. Typically, the course contains statistical analysis of data, different types of sensors, signal conditioning, and computerized data acquisition systems. This content is organized into nine topics: 1) Calibration, accuracy, errors; 2) Data Acquisition system; 3) Op-Amps; 4) Strain Gages; 5) Temperature sensors; 6) Signal conditioning; 7) Linear motion transducers; 8) RPM sensors and 9) Flow sensors and CNH.

Our 2-year consecutive study used three different teaching methods: (1) traditional mode; (2) combined mode; and (3) full PBL. In the year 2001 course, we used the traditional content-based instructional method in the first half of the course. The first test was given at this time. After that we used a combined mode of teaching which introduced a PBL module for the temperature measurement unit and implemented the rest of the second half of the course with a traditional content based teaching. The students mainly learned the temperature measurement component on their own by doing a PBL project. The second test covered materials taught in a combined mode including both traditional and PBL. The tests had numerical problems and multiple-choice concept questions. The PBL project was evaluated based on a group report (30%), group presentation (10%), individual research work (30%), individual critical evaluation of PBL (15%), and peer evaluation (15%).

In the year 2002 course, we used a fully PBL-based teaching method. We call this as full PBL mode. The course consisted of two 50-minute recitations and one 2-hour laboratory per week. In this mode, students were given 13 assignments in the recitation part and 7 lab problems in the lab part. Both the assignments and lab problems were open-ended real-life problems. Each of them emphasized the concepts and contents corresponding to last year's course to ensure the same coverage of the course. For the assignment, the students were asked to do research on the problem and to submit the answer to the problem first. Then the problem was discussed in the class. Finally the students submitted the revised answer for each assignment. In the labs, the students were divided into different groups. The very last lab problem was designing a robot using Lego RCX system. In the first phase of this lab problem, the student-designed robot should travel in a 2 feet by 2 feet square along the marked white line and come back to the original position. In the second phase of the problem, an empty pop can was placed on any place of the trip. The robot should detect and remove the can and finish the trip. In the two phases, whichever robot used the least time finishing the trip was the winner for that phase. The students were given the Lego RCX systems, sensors, and programming software. Their responsibilities covered from learning how to use the system to designing the system. The exams were controlled in the same format and same difficulty as last year.

In the implementation of PBL in our course, we also had representatives from some of the world's leading instrumentation companies in support of our teaching experiment. They were from Rosemount, MTS, Medtronics, and Phoenix International (a subsidiary of John Deere). In line with our work, three experienced educators (over 14 years of teaching experiences) from the higher educational institutions also were consulted. They were from the University of North Dakota, Minnesota State University at Mankato, and the Department of Agriculture and Biosystem Engineering at North Dakota State University. Based on the experiences of industrial representatives and educators, we collected input from them regarding pros and cons of PBL and suggestions for PBL implementation in engineering measurement class.

Results

Comparison of the Three Instructional Modes The quantitative data from the two years' courses are illustrated in Table 2. These assessment data indicate that students' regular test scores on the combined mode did not decrease compared with the traditional mode. In the full PBL mode, the test scores were even higher than both combined mode and traditional mode, even though students learned most of the material themselves. The performance on the PBL project in the combined mode was significantly higher than the test performance in traditional mode. The results indicate that we must evaluate PBL courses in multiple ways using test and projects. This concept is in line with the comments made in the Kuwana[17] report, "PBL also sparks concerns about how [the] faculty is to assign individual grades. Those who are concerned about scoring student achievement might look to industry for guidance. On the job, people's competency and contributions are evaluated in a number of ways, including portfolios, peer reviews, self-assessments, and final product."

Table 2. Data from the Two Tests and PBL Project

	ITEMS	Average Score	Max. Possible Score	Std. Dev.	Average Score in Percentage
2001 Course (N=43)	Test – 1 Total (Traditional Mode)	20.4	30	5.1	68
	Test – 2 Total (Combined Mode)	22.8	30	4.1	76
	PBL Project	27.0	30	1.1	90
2002 Course (N=35)	Test-1 Total (Full PBL)	78.3	100	9.6	78
	Test-2 Total (Full PBL)	80.2	100	9.5	80

At the end of the semester, students were asked to compare some of the items related to enhancing their skills in a full PBL class, and/or a Combined Mode class with other similar, traditional classes. The results of the feedback are given in Table 3. They indicate that both full PBL and combined mode teaching appear to have an advantage over the traditional method for enhancing the desired skills. However, students like the combined mode better than the full PBL mode. Fig 2 shows one group of students working on the Lego system. Fig 3 shows students testing Lego Robot traveling along the 2 ft by 2 ft square marked by a while line.

Fig. 2 Students were Working in Group on Lego System

Fig. 3 The Lego Robot was traveling along a 2 ft by 2 ft squre

Table 3. Student Perception of Skills Developed in a PBL and Non-PBL Class (N=42)

Skills	Full PBL	Combined Mode	Traditional
Ability to work in a team, like on a real job	4.03	4.1	3.3
Ability to solve real-life, open-ended problem	3.86	4.1	3.2

Note: 1. Average values of PBL and Non-PBL classes were statistically different at $\alpha = 0.001$.
2. Rating scale: very good (5), good (4), neutral (3), poor (2) and very poor (1).

The course objectives have been defined on the basis of the ABET engineering criteria 3a-3k and the institutional mechanical engineering program objectives. A survey was conducted among students by the end of semester for the full PBL course to evaluate if the course objectives had been achieved. The student assessment results are compared with the faculty assessment data, as shown on the course outcome assessment matrix in table 4.

Table 4. Course Outcome Assessment Matrix (Full PBL Mode)

No.	Course Outline Students will have demonstrable knowledge of being able to:	Faculty Assessment Sources	Faculty Assessment (1-5)*	Student Assessment (1-5)*
1	calibrate an instrument and determine its accuracy, sensitivity, etc.	Tests	3.79	4.31
2	apply principles and characteristics of different instruments used for the measurement of strain, force, temperature, velocity, etc., to a specific situation	Tests	3.89	3.86
3	design and build signal conditioning device using an operational amplifier	Tests	3.86	3.72
4	use and select a data acquisition system for a given application	Tests	3.79	3.72
5	solve real-life engineering measurements problems by thinking creatively and critically	Lab Reports	4.56	3.86
6	communicate the results in writing	Lab Reports	4.56	3.83
7	work effectively in a team environment	Peer and Self Evaluation, and Observation in Lab	4.50	4.03
Average			4.14	3.90
Standard Deviation			0.38	0.21

*5 = highest score, 1 = lowest score

The discrepancies between student and faculty assessment results clearly show the different perceptions of course outcomes by these two different groups : Among the 7 items being evaluated, item 1 (calibrate an instrument and determine its accuracy, sensitivity, etc) is the highest in students' assessment, but the lowest in faculty assessment; item 5 (lab reports) and item 6 (communicate the results in writing) are below the average in students' evaluation, but the highest in faculty assessment. It means that PBL teaching needs fine turning, requiring proper communication between faculty and students, and it must be student-oriented by considering their specific background and personal characteristics. From our observations, students liked the combined mode class better than the full PBL class. However, when the course was switched to the full PBL mode, the complaints became obvious, and the working load increased significantly.

Survey Results The survey results of industrial representatives, the experienced educators, and the students from our course demonstrated quite similar concerns and views (table 5).

Discussion

a.) A primary goal of PBL is to prepare students to be self-directed, lifelong learners and practical problem solvers.[18] Our data confirmed the published data from other researchers that PBL has strong positive effects in promoting students' problem-solving skills[19] and their ability to transfer these skills to real-world situations,[20-22] without compromising their exam performances.

Table 5. Pros, Cons, and Suggestions for Implementing PBL in a Class

Responders	Pros	Cons	Suggestions
Industry	1. Team work. 2. Training for real life practice. 3. Training for working independently 4. Students fully engaged	1. Takes time 2. May not cover all of the necessary knowledge 3. Different students may develop with different aspects of the lessons without a whole picture in understanding the problem project	1 PBL is not the answer to all problems 2. Balance between depth and breadth. Breadth is important 3. Using combination of PBL and traditional methods is necessary. 5. Have students with basic, expected level of knowledge to ensure the breadth covered by the course
Experienced Educators	1. Closer to the approach of engineers in real life 2. Work independently 3. Greater learning responsibility on students 4. Team work & effective communication	1. Takes time 2. Less efficient & less comprehensive to cover material in a course 3. Can be negative if students or team is not interested or passive	1. Design the engineering curricula to include a balance between courses which emphasize PBL and traditional teaching methods, or develop this balance within a course 2. Balance breadth vs Depth 3. Traditional methods are good for basic theory, concepts; PBL could be well combined with lab exercises 4. Be careful of the possible damage of instruments, “magic smoke” of the circuits; prepare spare equipment and materials.
Students	1. Learn better with hands-on experience 2. Easier to retain information 3. More like real life work and realistic experience 4. Hone communication and team building skills in group work 5. Students are forced to interact & take active roles 6. PBL requires students go gain additional knowledge through research 7. PBL makes students professionals instead of bookworms	1. Takes time; less efficient 2. Less topics covered; some information could be missed. 3. Passive students would have difficulties motivating to discover things on their own 4. Difficulty in students’ transition from traditional learning method to PBL 5. Harder in larger group; it takes longer 6. Hard in time scheduling	1. More directional questions from instructors, but not too many, to make sure the students are clear what is expected of them 2. Use combination of traditional & PBL 3. Background info is important before introducing the problem 4. Control the difficulty of the problems 5. PBL should not be used to introduce new material; it should be used to develop depth of understanding of material that has been previously imparted through traditional pedagogy 6. Instructor needs to be a good mentor & coach to ensure the students staying on the right track 7. The problem set should be designed to cover all of the fundamental concepts 8. Each group member should understand the whole project

b.) However, we cannot take PBL as a panacea to cure all of the current educational problems. Faculty, industry representatives, and students all agree with the use of appropriate combinations of traditional and PBL methods, at least in the period before the students are fully accustomed to the PBL. The traditional content-based method is good for teaching basic theories and concepts, like Kirchhoff's law, instead of leaving students to discover; the PBL is more suitable for teaching lab related concepts and exercises. Although PBL is considered to satisfy the requirements of ABET engineering criteria,[16] the surveyed educators still suggested that our engineering curriculum might need to be revamped to balance the courses taught in traditional method vs PBL or to develop the balance within one course depending on its specific contents and levels instead of making everything in PBL.

c.) Critics argue that PBL sacrifices breadth for depth.[18] In our course syllabus, the problem set was deliberately designed to cover all of the topics and basic concepts. However, the students were still worried about the missing information and covering lesser topics. Numerous studies support the perspective that PBL promotes more in-depth understanding of content than traditional methods, which is also confirmed in our study.[23-25] The old dilemma of depth vs breadth seems more problematic.

d.) Another concern about PBL is the lack of knowledge acquisition that occurs in a PBL environment.[26-27] However, Hung and colleagues'[18] review of PBL research suggests that this concern is unwarranted. In fact, higher-order thinking and knowledge acquisition can coexist and even bolster each other.[18] In a traditional or content-based approach, the emphasis is on covering as much material as possible, and that emphasis often creates difficulty for instructors. The huge quantity of material also makes it impossible for students to develop deeper understanding of the subject matter. We suggest that teaching basic theories and concepts in the traditional way, which is fast, could provide an index for students' future work needs; while important topics, which need more deep understanding, could be implemented as PBL.

e.) Making a transition from a traditional lecture-type class format to a PBL format is fairly complex for both faculty and students. On the challenging side, not all students (or colleagues) like this change; the process is time-consuming; and there are very few "good" problems and assessment tools. Research also shows that the initial transition from the traditional to PBL pedagogy may be a difficult adjustment for students. Students are concerned about content coverage in a PBL environment,[21, 24, 26] which is also reflected in our survey. Another reason for students' frustration might be the newness of students' roles in PBL.[28] The shift of students' roles requires the students not only to adjust their own learning style but also to redefine their roles in the learning process.[29-30] On the positive side, Schultz-Ross and Kline[27] found that students' discomfort and dissatisfaction levels decreased significantly by the end of a course. Our study confirmed the reports from other fields that students considered PBL to be effective in enhancing their confidence in judging alternatives for solving problems,[30] helping them improve communication skills,[31] improving their learning of basic science information,[32] and developing thinking and problem-solving skills.[26] It is still a long-term growing pains for the transition process in higher education. Professors must help students make a smooth transition to PBL by explicit students' roles and responsibilities within a PBL framework.[18] As stated by Barbara Duch, Director of the Science and Education Resource Center at the University of Delaware, "Would I return to a traditional lecture format? Not a chance. The excitement and energy of a room of students working in groups, teaching each other, challenging each other, and questioning each other is what I'll always want to see in my classroom."[17]

f.) The instructor's role in PBL process could be characterized in numerous terms: a facilitator,[33] pointing students in the right direction mainly by asking questions (as in the Socratic style); a tutor,[34] allowing students to make mistakes while helping them stay on the right track; a coach,[35] motivating students to become fully engaged in play while keeping them within the boundaries of the game; a learning manager;[36] a project supervisor in the student-supervisor interface;[37] and a guide by the side.[38] However students' complaints remind us that the transitioning is not easy, especially for those passive students. The different conceptions of the course outcome between faculty and students (Table 4) confirmed the report from Lieux[26] that an inconsistency existed between the students' perceptions of their work and their actual performance. Lieux found that the PBL group perceived that they had learned less than the lecture group. However, the results of the students' final examinations did not agree with their perceptions about learning. Our results also revealed no decrease of the PBL students' performance in exams. The discrepancy of the course outcome assessments between faculty and students may also suggest more student-tailored interactions by instructors to fine-tune the pace and to be more group and student oriented. Effective communication with students is essential if tutors are to successfully guide the students' learning processes throughout PBL.[18] Some researchers suggests that when tutors are not actively engaged in guiding students in a cognitively congruent way, students feel that their learning experiences suffer.[39] Wilkerson's[40] findings seem to support the importance of tutors as metacognitive models.

g.) Numerous papers have reported the concepts, pros, cons, and implementations of PBL. Very few address how to design the real-life engineering problems for PBL and control the problem size and difficulties. In our Engineering Measurement course, we used Lego RCX to design the problems. The problem given to the students had been solved before the course by our teaching assistants to ensure its difficulty and anticipate its potential problems. From our experience, the Lego RCX System demonstrated its superiority as an ideal platform in designing real-life problems in measurement and control, in controlling the problem difficulties, and in inspiring students' interest in class. It could be used by professors who are novices in PBL implementation.

h.) From our observations, when the group size increases to more than five members, the organizing, scheduling, and discussing process could be less efficient, especially because many students work several hours per week on other paid jobs. Three to five might be an ideal number for a group size.

i.) All group members must be accountable for doing their share of the work and for mastery of all of the material to be learned. Methods in Cooperative learning (CL) have been proved effective and should be performed to help solve this problem.[41-43] The principal method of assuring individual accountability in cooperative learning is to give individual examinations covering every aspect of the assignment or project. One way is to define a *group process monitor* rotated among team members in different projects to verify that each team member understands each part of the final report, not just the part for which he or she was primarily responsible. By the end of each problem/project, each team gives a written report and the instructor arbitrarily designates which group member presents which part of the project. The instructor completes the discussion by highlighting important items either missed by students or not addressed by the current problem. In this way, passive students have to fully engage in the group work.

Conclusions

Wilbert McKeachie and Graham Gibbs,[44] in their tenth edition of *Teaching Tips*, say, "Problem-based Learning is one of the most important developments in contemporary higher education." PBL is used in most medical schools, and it has the potential of having a profound effect on undergraduate education. Patricia Cross,[45] in her American Society for Engineering Education (ASEE) 1991 Annual Convention keynote address, said, "Teaching is in a primitive state of development, and improvement can take place all along the line. The real intellectual challenge of teaching lies in the opportunity for individual teachers to observe the impact of their teaching on students' learning. And yet, most of us don't use our classroom as laboratories for the study of learning." As educators, we should take up the challenge of experimenting with PBL and assess its impact on student learning.

The main purpose of academic assessment is to review the present situation and make necessary changes for improving the education process.[46-47] This assessment study indicates that the PBL method, either taught in full PBL or combined with the traditional method, significantly improves important skills such as analyzing and solving open-ended, real-world problems; working cooperatively in teams; and communicating effectively, verbally and in writing. In comparison of the traditional, combined PBL, and full PBL teaching methods, we find that combined mode is more welcomed than full PBL mode, partially due to the students' curiosity and less working load for students. Depending on the contents of a course, different topics could be used in different instructional modes for better results and student satisfaction, at least before students feel fully comfortable with the PBL. Our study, like many other studies, also indicates that there was no gain in students' performance on standard tests and exams. However, it is important to note that students' performance on the standard tests and exams did not decline either. The Lego RCX System demonstrated its superiority as an ideal platform in designing real-life problems in measurement and control, in controlling the problem difficulties, and in inspiring students' interest in class. Based on the above results and the support from the National Science Foundation, we are planning to increase the number of PBL exercises in the measurement course and develop educational materials for other instructors. Representatives from several leading industry corporations are supportive of the PBL method and have agreed to provide real-life problems. More problems using Lego RCX could be designed to form a PBL problem database for future reference in engineering measurement and control courses. The PBL materials for the measurements course will be tested at four other universities. We believe that other educators should also consider testing the PBL method of instruction in different engineering subjects, and the implementation and assessment approach used in this paper can easily be applied to study its impact on enhancing student learning in their course(s).

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