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# Student Experiences with Problem-Based Learning: Findings from an Electrical Engineering Course*

SONGXIN TAN
Department of Electrical Engineering and Computer Science, South Dakota State University, 451 Stadium Road, Brookings, South Dakota, 57007, USA. E-mail: songxin.tan@sdstate.edu

ZIXING SHEN
Department of Accounting and Information Systems, New Mexico State University, 1780 E University Ave, Las Cruces, New Mexico, 88003, USA. E-mail: zshen@nmsu.edu

The engineering field is changing rapidly. Engineers need to have multiple knowledge, skills, and abilities (KSAs) to stay current and relevant. Problem-based learning (PBL) can prepare engineering students to develop KSAs. The extant PBL research at the course level primarily examines the effects of PBL on learning outcomes measured by instructor-developed performance metrics and student self-reports. Thereby little is known about student perceptions of PBL learning experiences and processes. This study aims to bridge this gap. We conduct a case study on student learning experiences with PBL in an electrical engineering course. The quantitative and qualitative analyses of questionnaire data show that students had an overall good experience with PBL and reported positive effects of PBL on independent and interdependent learning. The student-centered approach helps develop a shared understanding between students and the instructor and contributes to the empirical knowledge of the learning experiences and processes of PBL. The study, therefore, provides engineering educators with deeper insights into PBL and practical guidelines in designing and implementing PBL in their courses.

**Keywords:** problem-based learning (PBL); student perspective; learning experiences; learning processes; case study; electrical engineering

## 1. Introduction

The engineering field has witnessed rapid advances in technology, research, and practice in recent decades. Engineers are faced with the daunting task of staying abreast of the innovations and changes. The engineering field is also seeing shifts in the types of engineers needed to emerge from college. Engineering education needs to equip future engineers with the ability and quality to adapt to the fast-moving engineering landscape [1] and to participate as active and effective members of the global society [2]. As such, engineering students should possess multiple knowledge, skills, and abilities (KSAs) that cover technical competency of domain knowledge, analytical skills and critical thinking abilities, and social skills in communication, teamwork, leadership to succeed in a team-driven, culturally, and ethnically diverse, and globally oriented workforce [3].

Yet, studies have shown that engineering education falls short in producing engineers with these KSAs and preparing them for the rapid changes in the engineering field [3–5]. Curricula improvements and pedagogical innovation are needed to instill multiple KSAs in future engineers. In fact, there recently has been a shift from lecture-based teaching to more learner-centered instruction, such as problem-based learning (PBL), in engineering education [6]. PBL is an active, inductive, student-centered approach that uses or simulates real-world, authentic, contextualized problems to drive learning [7]. Regarded as one of the most significant pedagogical innovations in higher education [8], PBL has gained tremendous popularity since first developed in medical education in the 1950s. It is now adopted in almost every educational discipline, including natural science, e.g., [9], social science, e.g., [10], engineering, e.g., [11], and business, e.g., [12].

PBL is particularly instrumental in developing and attaining KSAs that future engineers need to possess to be a competitive force within the field [5]. Not surprisingly, it is widely used in engineering education [13]. PBL is always practiced as a combination of PBL projects and traditional lectures (TL) in engineering education. PBL projects have a special appeal to engineering courses, given the hands-on and applied nature of the engineering disciplines. TL help students gain a conceptual understanding of the learning materials, many of which are intellectually difficult for them to learn independently.

A considerable amount of research has been directed toward PBL in engineering education. A recent review by Chen and colleagues [13] reveals that the PBL is implemented at different levels such as course level, curriculum level, and cross-course


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level. At the course level, the PBL project is used as a teaching tool in one course for one semester. The extant PBL research at the course level has been primarily on the design and implementation of PBL, e.g., [14] and the evaluation of its effect on learning, e.g., [15]. The evaluation has been mainly based on instructor-developed performance metrics such as PBL project presentation, report, and exam, e.g., [16]. While instructor-centered assessments are valid, student perspectives are also valuable in understanding the effectiveness of PBL in developing KSAs [11, 17] and PBL learning activities [18]. Over the years, a growing number of empirical studies have been tapping into student-perceived PBL learning outcomes, e.g., [19–23]. This study continues this line of research on the student perception of PBL. Specifically, we conduct a case study to examine how students perceive their learning experiences with PBL in an electrical engineering (EE) course. Our study improves the empirical understanding of students' experiences with PBL, complements the existing PBL research in engineering education, and helps the engineering educators to materialize the educational benefits of PBL.

## 2. Related Literature

### *2.1 Theoretical Underpinning of PBL*

At the core of PBL is the idea that the appropriation and assimilation of knowledge and skills ultimately can only be accomplished by the learners, not the teachers [24, 25], because "true learning is based on discovery guided by mentoring rather than the transmission of knowledge" [26]. Accordingly, PBL focuses on student learning instead of instructor teaching. Students acquire knowledge and skills through the instructor-staged problem [8], which is curriculum-based, open-ended, and targeted for real-world applications. As they learn to gather, synthesize, and analyze information on their own to solve the problem, students take the initiative and responsibility for learning with the guidance and mentoring from the instructor. Therefore, PBL differs from passive lecturing and memorization-based teaching by placing students at the center of the learning process and applying authentic, relevant problems to raise compelling learning issues and stimulate active student learning [27].

PBL is grounded in the constructive tradition of cognitive learning theories [28]. For example, the epistemology of constructivism, which studies the social mediation of knowledge construction, stipulates that the learner's information process is at the center of learning [29]. This is in line with PBL's emphasis on the pivotal role of active student engagement in the learning process. Based on the constructivist theory of teaching and learning, contextual learning recognizes that adult learners more readily understand and assimilate instructions embedded in a context that they are familiar with [30]. That is, learning takes place when teachers can present learning materials in a way that students can relate to their own experiences. This proposition is well integrated into PBL, where experiential learning and active learning are critical in solving the problem that is of direct links to real-world applications.

In a similar vein, research on memory shows that matching context enables knowledge recall [31]. Notably, the instance theory in cognitive psychology suggests that pattern recognition (i.e., decision making based on the similarity of the current instance to the prior one) facilitates learners to acquire problem-solving skills. The key to knowledge retrieval is to provide a context similar to that at the time of learning. For example, a study on divers found that word lists learned on land recalled better on land, whereas these learned underwater recalled better underwater [32]. PBL facilitates instance-based reasoning [33] and uses real-world problems to provide a meaningful context for knowledge recall.

Other inquiry-based learning theories also support PBL. For example, Bruner's discovery learning theory posits that students learn best when discovering facts and relationships for themselves [34]. Learners often do not absorb what is taught to them well. But they learn better when they actively seek answers and solutions. Hunt [35] proposes that confrontation of meaningful yet poorly understood problems, an inherent feature of cognitive learning, drives student learning. Aligned these theories, PBL presents students with vaguely described problems [16], encourages them to build on past experiences and knowledge, use their intuition, imagination, and creativity, and search for new information to discover facts, correlations, and new truths.

### *2.2 Prior Research on PBL in Engineering Education*

PBL needs to be carefully designed and implemented to reap its educational benefits. Crafting the problem is critical to the PBL project [7]. Ideally, the problem should be technically complex, covering a range of relevant topics. In the meantime, it should also challenge students to engage in in-depth learning to comprehend the materials under study. The problem is often interdisciplinary. PBL projects can be implemented in multiple ways [36] based on the number of problems. A single-module PBL has only one problem, and a multi-module PBL implements two or more problems.

PBL has made inroads into engineering education [37, 38]. It has been studied in various courses in many engineering disciplines, including biomedical engineering, e.g., [39], civil engineering, e.g., [14], electrical engineering, e.g., [6], industrial engineering, e.g., [40], mechanical engineering, [15], and interdisciplinary engineering areas, e.g., [41]. The literature had adopted two approaches. One examines PBL from the instructor's angle. Research in this tradition examines the effects of PBL on the acquisition of technical KSAs via instructor-developed metrics (e.g., grades), e.g., [6] and the instructor's experiences with PBL in implementing PBL in the course, e.g., [40]. The other perspective is centered around students. In this research stream, some studies investigate the factors that affect the student perceptions of PBL. For example, Jaeger and Adair [22] analyze the influence of students' personal situation, general interest in engineering, and ability to succeed on their perception of PBL. Others explore student perceived effects of PBL on developing technical KSAs [20], non-technical KSAs [11], or both [21].

The literature review reveals the lack of empirical research on student perception of their learning experiences in PBL. As a result, little is known empirically about student learning processes with PBL. The learning process is the antecedent of learning outcomes [42]. In addition, student opinions and feedback can help develop a shared understanding between students and instructors, produce new insights into the student learning process, allow instructors to adjust and prioritize to facilitate learning, and ultimately promote more effective teaching and learning [43]. As such, it is imperative to understand student learning experiences and processes with PBL. The following research question guides our study: How do students perceive their learning experiences and processes in the PBL course?

## 3. Methodology

### *3.1 Case Description*

The interpretive case study research method [44, 45] was chosen to answer our research question. The interpretive case study method was found appropriate for at least two reasons. First, it provides a deep insight into "the complex world of lived experience from the point of view of those who live it" [46]. It enables the generation of empirical knowledge of student perceptions of PBL learning experiences, an important yet under-researched area. Second, this study has the "how"-type research question. The interpretative case study research method is preferred to answer "how?" and "why?" questions [45]. It has been commonly used in research on education (e.g., [47]).

We conducted our case study in an upper-level EE course, Digital Image Processing (DIP), in a public university (University) in the Mid-West United States (US). DIP is a three-credit-hour technical elective offered to juniors, seniors, and graduate students every fall semester. The course had been taught in TL before PBL was implemented. The first author taught the course when this study was conducted. He had also taught the course in TL modality for more than five years before this study.

A 3D imaging project was designed and implemented as a PBL project in the DIP course and replaced the previous projects used in the TL format of the course. The project used a digital projector for fringe projection and a digital camera to acquire the fringe images. These images were then processed by a computer to retrieve the 3D profile of the object. The project description is shown in the Appendix. Fig. 1 illustrates the major steps of the project. The 3D imaging project presented an ill-structured problem linked directly to practical applications in digital image processing, computer vision, and robotics vision.

The PBL project was distinct from previous TL projects in the DIP course. First, while the topics needed for the project were covered in lectures for the TL projects, they were not for the PBL project. The PBL project required students to independently learn these topics (e.g., phase retrieving, phase unwrapping, and Gamma correction). Second, the PBL project addressed an open-ended problem and was much more technically complex than the TL projects. Each step of the PBL project, as shown in Fig. 1, could be used as a stand-alone TL project in terms of project breadth and depth. Furthermore, the PBL project had multiple technical approaches to the desired outcomes. In contrast,

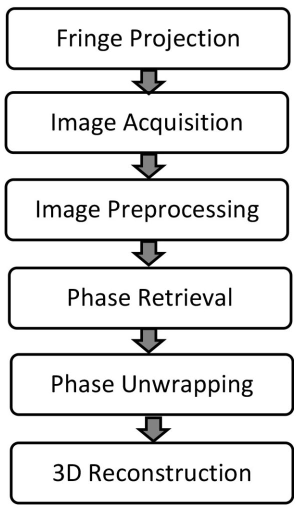


**Fig. 1.** The block diagram of the 3D imaging project with six major steps.

**Table 1.** Class Time and Grade Allocation in the PBL Course

| | TL | PBL |
|---|---|---|
| **Class Hours** | 78% | 22% |
| **Assessment** | 55% | 40% |

(Note: Class participation was neither TL nor PBL and accounted for 5% in the assessment.)

the TL projects had only one solution. In sum, the PBL project represented the open-problem-based and learner-centered approach [48].

The PBL project was introduced in the second half of the 15-week semester. Students worked in teams of two to three members of their own choice. Therefore, students participated in a small group-based single module PBL. The majority of the class time was allocated to TL, given that students had no prior experiences with PBL. This would aid manage student anxiety and resistance to PBL and facilitate the transition. TL was reduced from 36 hours to 28 hours to provide more class time for the PBL project. As shown in Table 1, the ratio of class time on TL and PBL is approximately 3.5:1, and the weight on grading is approximately 1.4:1. Before the PBL project started, the instructor went over the project requirements and explained how to conduct the project. Such clarifications helped students understand the nature of the PBL project and its differences from the projects that students had previously.

During the class time dedicated to the PBL project, students were either in the laboratory or in the classroom with the instructor. The instructor answered the project-related questions raised by the students and assisted students with their understanding of the project. The instructor only provided general guidance and informal feedback without direct involvement in the management and solution of the project. The PBL project had two deliverables – an oral presentation and a written report, both due in the last week of the semester.

Last but not least, the instructor took measures to ensure that actual learning took place in the longitudinal study. The PBL project was the instructor's research topic. It was carefully designed and developed to suit student learning. First, the instructor ensured that the project solution was not readily available online. In fact, there were minimal online resources available at the time of the study. Second, steps were taken to minimize the solution leakage. For example, the exam papers were never returned to the students. The instructor always requested the students not to hand over their solutions to future students. In addition, it was practically difficult, if not impossible, for students to pass the project solution, given the technical complexity and breadth of the project. Furthermore, the class average grades over the four-year PBL study period were 85.1, 87.8, 85.9, and 84.9. There is not a clear upward trend. As a result, we were confident that students' learning experiences were authentic.

### *3.2 Questionnaire*

Following earlier research that solicited student input, e.g., [21], we designed the questionnaire to collect student learning experience with PBL. As shown in Table 2, the questionnaire consisted of eight structured questions. Q1 gauged students' general attitude towards PBL, which the student performance data could not capture. Based on earlier research on learning outcome [6], motivation [49], independent learning [50], problem difficulty [51], and efforts [52], Q2 to Q6 assessed students' PBL learning experiences on different aspects of PBL. The appropriate ratio of TL and PBL is under-researched [16]. Student input can guide more effective PBL implementation in the future. Q7 and Q8 sought students' input on their preference of PBL and TL and the ratio they would like to have in the PBL course, respectively. A five-point Likert scale was used for Q1–Q7, where 1 represented strongly disagree, 2 for disagree, 3 for neutral, 4 for agree, and 5 for strongly agree. Q8 took a numeric value from 0 to 1, indicating students' preferred PBL percentage in the PBL course.

The questionnaire also contained one open-ended question that asked students to reflect on their PBL learning experiences. Students were encouraged to share their positive and negative experiences in the PBL project and explain their

**Table 2.** Survey Questions

| | |
|---|---|
| Q1 | How do you like Problem Based Learning (PBL) project in this course? |
| Q2 | Do you think that you learned more in the PBL project than Traditional Lecturing (TL)? |
| Q3 | Do you feel that the PBL project motivated you to learn? |
| Q4 | Do you think that the PBL project improved your independent learning skill? |
| Q5 | Do you feel that the PBL project was more difficult than TL? |
| Q6 | Do you feel that you made more effort to learn in the PBL project? |
| Q7 | Would you like to have a course with PBL only and without TL at all? |
| Q8 | If both TL and PBL are used in this course, what would be the preferred percentage of PBL for you? |

responses to the previous eight questions. Finally, student demographic information, including gender, academic standing, prior experience with PBL, and domestic or international student, was collected.

### *3.3 Data Collection*

For four consecutive years, the questionnaire was given to all students enrolled in the DIP course at the end of the semester when the PBL project was completed, but the project grades were not released to the students. This timing was chosen to improve the accuracy of students' responses when their PBL experiences were still fresh and to reduce the influence of grades on students' opinions. Participation was anonymous and voluntary without any extra incentive. A total of four questionnaires were collected. Of the 54 students who completed the PBL courses in the four years, 46 returned the questionnaire. The initial response rate was 85%. The screening of the 46 questionnaires found that five did not answer all questions (that is, one or more questions from Q1 to Q8 were unanswered). Those incomplete questionnaires were excluded from further analysis. The 41 valid questionnaires were used for quantitative data analysis. The usable response rate was 76%. Table 3 shows the respondent's demographic information. Of the respondents, none had prior experiences with PBL, and the majority were domestic undergraduate students. This was representative of the general population of students in the EE program of the University. A total number of 38 student reflections were obtained from the questionnaire. That is, 70% of the students who completed the PBL project provided their thoughts.

### *3.4 Data Analysis*

The data from the eight structured questions were analyzed using descriptive statistics, which included frequency distribution, mean, and standard deviation. The responses to the open-ended self-reflection question were analyzed in a multi-step process. First, the data were transcribed into a word document. Both authors read the text several times to become immersed in the data, which is critical in analyzing qualitative data [44]. The open-coding technique [53, 54] was then used in the data analysis. Specifically, each author independently went through the text and grouped the data in a way that made sense. Categories emerged after each author broke down, examined, compared, and conceptualized the data.

Next, the authors shared and looked into each other's initial coding. They then worked jointly to resolve the differences in their categorizations. For instance, the comment "I learned a lot from my peers in the group!" was put into the "Enabling Learning" category by one author and "Peer Learning" by the other. The two authors discussed how and why they came up with the coding. As the student learned from others in their group, this comment was definitely under "Enabling Learning". But multiple factors enable learning. After such discussions, the authors had a more exact concept definition and more precise differentiation. They agreed that the comment should be coded as "Peer Learning" under the theme "Enabling Learning". After the differences in coding were reconciled, the categories of codes were pooled together and arranged based on the themes that emerged from the analyses (e.g., the Peer Learning category is under the Enabling Learning theme).

## 4. Findings

### *4.1 Structured Questions*

The individual responses to Q1–Q7 were plotted in Fig. 2, which provides an overview of the data distribution. The response frequency on each Likert scale was counted and plotted in Fig. 3. The two figures show clearly that the responses to Q1 through Q6 are in higher value ranges in the Likert Scale from 3 to 5, whereas those to Q7 are mainly in the Likert Scale 1 to 2. Further examination of the individual responses shows that 71% of the respondents agreed (Likert Scale 4) or strongly agreed (Likert Scale 5) with Q1 (liked the PBL approach); 68% agreed or strongly agreed with Q2 (PBL enabled more learning); 83% agreed or

**Table 3.** Respondent Demographic Information

| | | Year 1 | Year 2 | Year 3 | Year 4 | Total | Percentage |
|---|---|---|---|---|---|---|---|
| **Gender** | Male | 12 | 10 | 6 | 6 | 34 | 83% |
| | Female | 3 | 1 | 2 | 1 | 7 | 17% |
| **Academic Standing** | Undergraduate | 11 | 9 | 6 | 7 | 33 | 80% |
| | Graduate | 4 | 2 | 2 | 0 | 8 | 20% |
| **PBL Experience** | Yes | 0 | 0 | 0 | 0 | 0 | 0% |
| | No | 15 | 11 | 8 | 7 | 41 | 100% |
| **Domestic Student** | Domestic | 10 | 8 | 4 | 5 | 27 | 66% |
| | International | 5 | 3 | 4 | 2 | 14 | 34% |

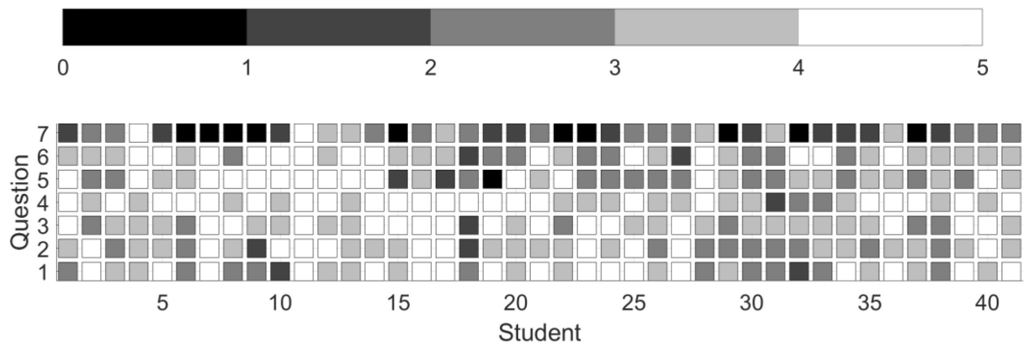


**Fig. 2.** The color-coded plot of individual responses to Q1-Q7. (Note: Grayscale bar shows the response on the Likert scale.)

strongly agreed with Q3 (PBL motivated learning); 93% agreed or strongly agreed with Q4 (PBL improved independent learning); 61% agreed or strongly agreed with Q5 (PBL was more difficult); 73% agreed or strongly agreed with Q6 (PBL required more efforts). Finally, only 20% of the students agreed or strongly agreed with Q7 (preferred PBL only), whereas 54% did not favor PBL only.

The individual responses to Q8 (preferred percentage of PBL) were mapped in Fig. 4. The histogram shows that one student preferred only PBL, and 40 students liked the combination of PBL and TL better. The preferred rate of PBL ranges from 10% to 100%, with a mode of 50%, a medium of 50%, and a mean of 50.7%.

Presented in Table 4 are the statistics of the mean and standard deviation for yearly and the aggregated four-year response data. The four-year means for Q1 to Q6 range from 3.85 to 4.46. Q4 [PBL improved independent learning) has the highest mean of 4.46. Q3 (PBL motivated learning), Q1 (liked PBL), and Q6 (PBL required more efforts) all have a mean above 4, with a value of 4.18, 4.07, and 4.04, respectively. The mean for Q2 (PBL enabled more learning) (3.90) and Q5 (PBL was more difficult) (3.85) are both close to 4. The high ratings indicate that students in the PBL course felt the PBL project was more motivating, challenging, and

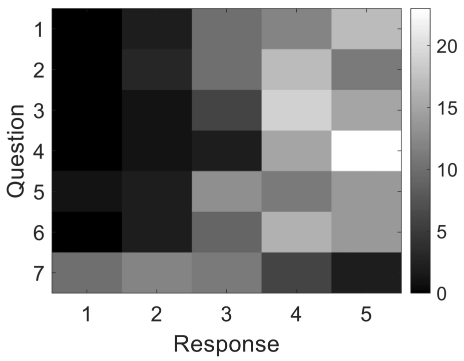


**Fig. 3.** Counts of individual responses to Q1- Q7 on the Likert scale. (Note: Grayscale bar represents the number of student responses.)

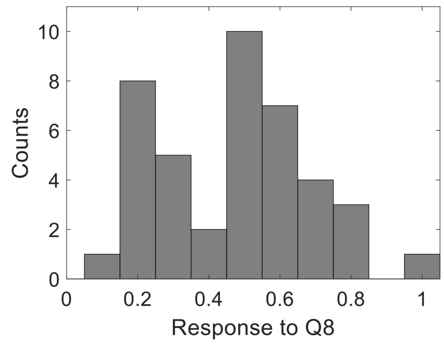


**Fig. 4.** Histogram of the individual responses to Q8, highlighting students' preference for the PBL approach.

**Table 4.** Descriptive Statistics of Students Response

| | | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 |
|---|---|---|---|---|---|---|---|---|---|
| **Year 1** | Mean | 3.93 | 4.07 | 4.27 | 4.67 | 4.4 | 4.47 | 2.53 | 0.516 |
| | Std | 0.93 | 0.85 | 0.68 | 0.47 | 0.95 | 0.62 | 1.41 | 0.229 |
| **Year 2** | Mean | 4.55 | 4.05 | 4.27 | 4.64 | 3.27 | 3.64 | 2.45 | 0.528 |
| | Std | 0.66 | 0.92 | 0.96 | 0.48 | 1.14 | 0.88 | 0.89 | 0.198 |
| **Year 3** | Mean | 3.5 | 3.44 | 4 | 3.63 | 3.63 | 3.69 | 2.38 | 0.385 |
| | Std | 1 | 0.77 | 0.5 | 0.86 | 0.7 | 1.09 | 1.11 | 0.168 |
| **Year 4** | Mean | 4.29 | 3.86 | 4.07 | 4.71 | 3.86 | 4.14 | 2.5 | 0.595 |
| | Std | 0.7 | 0.64 | 0.78 | 0.45 | 0.64 | 0.35 | 0.89 | 0.139 |
| **4-Year** | Mean | 4.07 | 3.9 | 4.18 | 4.46 | 3.85 | 4.04 | 2.48 | 0.507 |
| | Std | 0.93 | 0.87 | 0.77 | 0.71 | 1.04 | 0.87 | 1.16 | 0.21 |

demanding and improved their ability to learn independently. Overall, they enjoyed the PBL project and put more effort into learning. They believed that they learned more from PBL. This finding is in line with our earlier research [16] that shows that PBL significantly improved student project performance as measured by the project grade.

Despite the enthusiasm about PBL, students did not want PBL only, as revealed by Q7 (preferred only PBL). The students' preference for the combination of PBL and TL was also shown in their responses to Q8 (preferred TL/PBL ratio). The 4-year mean of Q8 is 0.507, denoting students would like to have an almost 50/50 split of TL and PBL. It should be noted that the PBL project only took 22% of the class time in this course. It was evident that students wanted more class time on PBL and less on TL.

The four-year standard deviations are all small, ranging from 0.210 to 1.16. Q8 (preferred TL/PBL ratio) has the lowest standard deviation of 0.210, indicating a consensus on the preferred percentage of PBL. Of the eight questions, only two have a standard deviation slightly above 1. Q7 (preferred pure PBL) and Q5 (PBL was more difficult) have a standard deviation of 1.16 and 1.04, respectively. While the students concurred more on overall attitude towards PBL (Q1) and the PBL project's effects on motivation (Q2), independent learning (Q3), learning effort (Q6), they disagreed a bit more on the difficulty of the PBL project and the preference for a PBL only class. This may be related to the preparedness of the students in the course. The less prepared students would consider the PBL project more difficult and prefer less PBL.

### 4.2 *Student Reflections*

Summarized in Table 5 are the findings from the qualitative analyses of the student reflections. They affirm as well as extend what is found quantitatively from the questionnaire. First, the student comments corroborate Q1 (PBL enabled more learning). Students reported that they learned more subject matter from PBL than TL, as exemplified by the statement that "the PBL project taught me more than the traditional plug and chug approach." Likewise, the Enabling Learning theme supports Q4 (PBL improved independent learning), as evidenced by the response that "There was a lot of self-learning. But I should never forget what I LEARNED HERE." The ability to think, act, and pursue one's studies autonomously is as valu-

**Table 5.** Themes from Student Reflections

| Theme | Category | Example Reflections |
|---|---|---|
| Enabling Learning | Learning materials | • I learned the most from the PBL project in this class.<br>• PBL project taught me more than the traditional plug and chug approach. |
| | Peer learning | • I had to teach other members after I learned myself.<br>• I learned a lot from my peers in the group. |
| | Self-learning | • I taught myself a lot through PBL.<br>• There was a lot of self-learning. But I should never forget what I LEARNED HERE. |
| Providing Motivation | Relevance to real-life | • I like the PBL approach because it combines real-world problem with hands-on experience.<br>• PBL is more practical and results in skills that can be applied when entering work. |
| | Challenged to learn | • I like the challenges of PBL. I think I actually learned better.<br>• PBL was hard but motivated me to learn. |
| Concerns and Issues | Technical difficulty | • PBL would have worked very well had the student had decent background on the subject matter.<br>• The PBL project was really difficult for me. |
| | Initial confusion | • I was a little confused when starting to work on the PBL project.<br>• Not quite sure about the project initially. Got better after some research. |
| | Time-consuming | • PBL is really time-consuming.<br>• PBL is not appropriate with the time constraint within a semester. |
| | Demanding workload | • I had to work really hard to finish the PBL project.<br>• The project required a tremendous amount of effort. |
| | Frustration in group work | • It was difficult to deal with group members, especially when one member had a different priority.<br>• My partner was not contributing enough to the project. |
| Suggestions | More connecting PBL project with lectures | • I would like the lectures to connect more to the PBL project.<br>• Like the initial lectures for starting the project. |
| | More examples | • I want an example with PBL.<br>• PBL could be improved by providing more examples. |
| | More class time for PBL project | • More class time is definitely needed for the project.<br>• I wish I had more time to work on the PBL project. |
| | Combining PBL with TL. | • Still believe traditional lectures are needed. But PBL is also important for problem-solving.<br>• Risky if PBL only. However, combining with traditional lectures can help students a lot. |

able as, if not more valuable than, the course materials that the students learn. In addition, students revealed that PBL promoted peer learning, as reflected in the comment that "I learned a lot from my peers in the group!" Peer learning enabled students to share knowledge, ideas, and experience.

The qualitative analyses also add to Q3 (PBL motivated learning) by showing how PBL drove learning. Specifically, the practical relevance of the PBL project provoked student learning, as one student put it, "(PBL) results in skills that can be applied when entering work." As they saw the real-life value of the PBL project, students took a personal interest in the PBL project, which kept them engaged. The technical contents of the PBL project also activated and sustained learning, as illustrated in the comment, "PBL was hard but motivated me to learn." The right level of challenge, designed into the PBL project, increased the curiosity and energy level and gave students a sense of accomplishment in achieving each project milestone.

Meanwhile, the open-ended responses captured students' concerns and issues with the PBL project. The comments on the technical difficulty, demanding workload, and time consumption are directly linked to Q5 (PBL was more difficult) and Q6 (PBL required more effort). Students also shared that they had initial confusion and were frustrated with group work. The lack of a clear understanding of the project at the beginning is common in engineering work, especially when the project has unstructured components that require engineers to define the problem and provide a customized solution. Moreover, engineers always work in groups to solve complicated problems. Working with people with different goals, personalities, skillsets, etc., is not always easy.

Finally, suggestions have emerged from the students' comments to address the concerns and issues mentioned above. Students wanted more support for PBL. Specifically, they wanted more guidance from the instructor. This need was understandable, considering that this was the students' first PBL experience. Students also wanted more time to work on the PBL project. They suggested that a mixture of TL and PBL would be better. This suggestion was in line with the quantitative findings from both Q7 and Q8.

## 5. Discussion

### *5.1 Research Contributions*

Our study contributes to a better understanding of the learning experiences and processes in PBL. Our study found that students liked the PBL approach, perceived more learning with the PBL project, and strongly preferred PBL. More importantly, our study provides explanations for such positive learning experiences. First, the PBL project in this study provided students with intrinsic motivation [35, 55]. The PBL project mimicked real engineering work characterized by creative problem-solving in a group setting. This authenticity prepared students for tasks and challenges in their future engineering jobs. Such elevated relevance stimulated student interests. The PBL project also motivated students by challenging them. It focused on the knowledge discovery by students and placed students at the center of the learning process, thus increasing student ownership and responsibility. Students took the initiative and were in charge of their learning. They defined and framed the problem, located resources, gathered information and materials, formulated investigation strategies, and implemented the solution. The more the students figured out on their own, the more they felt empowered to keep learning. They could repeat the pattern of discovery when applied to other interests and subjects.

Second, the PBL project provided opportunities for students to engage in independent learning (self-learning) and interdependent learning (peer learning). Independent learning was required to complete the PBL project. In creating their own learning paths, students engaged continuously in reasonable and reflective thinking focused on deciding what to do. As they immersed themselves in thinking, acting, and pursuing the PBL project autonomously, students comprehended the course materials, practiced their critical thinking ability, and sharpened their problem-solving skills. Alongside independent learning, the PBL project allowed students to engage in interdependent learning (peer learning). Students worked in a small group, taught, and were taught by one another. In these interactions, new ideas were developed, meaningful connections were fostered, and perspectives expanded. As they explained their ideas to others, students worked through new concepts and material and developed skills in organizing and planning learning activities, working collaboratively with others, giving and receiving feedback, and evaluating their own learning.

Last but not least, students believed that their meaningful learning experiences in the PBL project would last beyond the course. The KSAs, such as problem-solving, critical thinking, organizing, conflict resolution, and communication, developed in the independent learning and interdependent learning processes, would benefit students throughout their careers, as exemplified in such comments as "I should never forget what I LEARNED HERE" and "(PBL) results in skills that can be applied when entering work."

### *5.2 Practical Contributions*

Our study informs engineering educators of some key issues in the PBL learning process. First, student reflections corroborated the criticality of the problem in PBL projects. The problem should be authentic, challenging yet doable, and relevant to the course materials. The instructor should have a solid grasp of teaching materials as well as a good understanding of students to develop such a problem for the PBL project. The PBL project approach used in this study is different from project-based learning. Whereas students have learned through formal instruction to deliver the project in project-based learning [27], the PBL project requires students to acquire the necessary knowledge on their own to complete an ill-structured problem. This requirement posed additional challenges to students who were used to TL. As revealed in this study, students who had never taken any PBL course wanted more problem-related examples and more lectures connected to the problem in the PBL project.

Moreover, this study clarifies the instructor's role in the PBL learning process. PBL does not mean zero instructor involvement. Instead, in tandem with student accountability, the instructor's participation is vital [56]. This study reveals how the instructor can play a pivotal part in enabling and supporting learning in the PBL project. The instructor is a guide and an advisor, clarifying and helping students understand the problem vaguely described in the PBL project. This role is particularly crucial at the beginning of the PBL learning journey when students are not clear of the scope of and their responsibilities in the PBL project. This is especially true for students with no prior PBL experiences, as reflected in the students' comments on initial confusion in this study. Instructor guidance and advice can alleviate anxiety from not knowing what to do and getting students started with the project, thus paving the way for successful PBL.

The instructor needs to mentor and coach, encouraging and nurturing students to move the project forward. Otherwise, the students would be consumed with frustration and confusion and become reluctant to participate in the PBL project. This study indicates the importance of instructor support as students reported misunderstanding and underestimated the time and effort. The instructor should also explain the unique features of PBL learning and debunk the misconceptions around PBL. Instructor facilitation is essential to reduce student resistance, a major barrier for PBL success [56, 57], and change students' mentality from passive, instructor-driven teaching to active, self-directed learning.

Furthermore, the study sheds light on the ratio of PBL to TL. This study shows that, despite a TL dominant learning environment, the demanding learning materials, the lack of preparedness, students still wanted an increase in the PBL percentage from 22% to 50%. This suggests that a PBL percentage higher than 20% would be acceptable to students without previous PBL exposure. The rate could even go higher for students experienced with PBL. It is also recommended to gauge student acceptance and adjust the PBL-TL ratio accordingly to maintain a reasonable balance between PBL and TL.

### *5.3 Limitations*

This case study has several limitations. First, students reported their experiences in four different sessions of the same course. Although the instructor remained the same and made conscious efforts to keep the class consistent across the four years, there still might be minor variations in how the four sessions were conducted (e.g., class schedule). Such slight differences may affect how students perceived the PBL project, even though the mean and standard deviation of the yearly questionnaire data indicate the consistency in students' experiences. Future research can replicate this study in one single class session to remove any potential session differences. Future research can also triangulate this case study's findings with data collection methods other than the questionnaire. Though this study provided both quantitative and qualitative data, the questionnaire may miss other subtle qualitative data. Other data collection methods, like in-depth formal interviews, should be used to corroborate the validity of this case study's findings.

Sampling is another limitation of this study. The number of students who participated in the questionnaire was not very large. However, the sample size was adequate to provide valuable insights representative of PBL learning experiences and processes. Nevertheless, a larger number of participants might generate additional points of view. The study's respondents were seniors and first-year graduate students in an elective course. The study's findings, though valid, cannot be generalized to other engineering courses (e.g., required lower-level general education courses). Future research can work on required engineering courses, especially those with large enrollments, to validate further and extend what this study has found. As students in this study did not have any prior PBL experiences, it would also be interesting for future research to sample students with PBL experiences and investigate the role of prior PBL experiences. Finally, we did not offer differentiated PBL projects to the undergraduate and graduate students in the course. We did not expect much difference (e.g., preparedness for self-direct learning, learning motivation) between the two groups in our case study, as all graduates were first-year, and all undergraduates were seniors. There was no significant difference in their performance in the course at the time of the study. Yet, future research can explore whether the effects of PBL vary across undergraduate and graduate students and how it changes.

Only 17% of this study's respondents were female. This number, though smaller than 21.9%, the percentage of a bachelor's engineering degree awarded to females in 2019, is representative of the rate of female students in the EE program nationwide [58]. Nevertheless, future research can consider classes with more female students to explore whether there are gender differences towards PBL [59]. Finally, this study did not differentiate domestic and international students in the analyses. As research suggests that learning prevalent in tertiary education settings in some countries may not be congruent with PBL learning objectives [60], the effects of the learning mentality of students from different cultures on the PBL learning experiences deserve more empirical probe.

## 6. Conclusions

PBL has been gaining ground in engineering education, and more empirical studies are needed to understand the PBL learning experiences better. In this study, we surveyed juniors, seniors, and graduate students about their learning experiences in an EE PBL course. Students reported that the PBL project was more difficult and time-consuming. Nevertheless, they learned more from the PBL project and preferred a higher percentage of PBL. Our study shows that PBL can foster independent and interdependent learning and benefit students beyond the classroom. It also highlights the criticality of the problem design, the crucial role of the instructor, and the appropriate weight of PBL, thus providing engineering educators with practical guidelines in designing and implementing PBL projects. We hope that this study will stimulate more PBL research interest and effort from the student perspective to build a more comprehensive empirical knowledge base. We also hope that the positive feedback from students in this study will encourage more engineering educators to use PBL in their teaching practices to enhance student learning.

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## Appendix: PBL Project Description

Design a 3D Imaging System using Fringe Projection

Using 3D imaging to obtain an object's 3D profile has many practical applications in machine vision, robotics, metrology, industrial automation, biomedical imaging, and 3D printing. You are required to form a team of two students to design a 3D imaging system using fringe projection. Phase Measurement Profilometry (PMP) and Fourier Transform Profilometry (FTP) are two of the techniques you may want to consider. You are required to conduct a literature search, design a 3D imaging system to measure the 3D profile of a manikin face, and present the 3D profile graphically as a team. This is a problem-based learning (PBL) project. Detailed solutions will not be provided in the lecture. However, you will be given some class time to work on the project.

The following resources are provided for the project: an optical table, a digital camera, a digital projector, and a manikin head. You need to use your own laptop with Matlab to complete the project.

**Songxin Tan** is an associate professor of Electrical Engineering at South Dakota State University. He earned his PhD in Engineering from the University of Nebraska – Lincoln, USA. He has research expertise in problem-based learning, cognitive development, and technology use in learning. His research on learning and education has been published in journals such as *IEEE Transactions on Education* and *Journal of Education for Business*.

**Zixing Shen** is currently on the faculty of the College of Business at New Mexico State University. She earned her PhD in Management from Case Western Reserve University, USA. Her research on learning and education covers various topics such as problem-based learning, concept mapping, and learner engagement and utilizes both quantitative and qualitative research methods.