

Student Reactions to Problem-Based Learning in Photonics Technician Education

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ABSTRACT

Problem-based learning (PBL) is an instructional approach in which students learn problem-solving and teamwork skills by collaboratively solving complex real-world problems. Research shows that PBL improves student knowledge and retention, motivation, problem-solving skills, and the ability to skillfully apply knowledge in new and novel situations. One of the challenges faced by students accustomed to traditional didactic methods, however, is acclimating to the PBL process in which problem parameters are often ill-defined and ambiguous, often leading to frustration and disengagement with the learning process. To address this problem, the New England Board of Higher Education (NEBHE), funded by the National Science Foundation Advanced Technological Education (NSF-ATE) program, has created and field tested a comprehensive series of industry-based multimedia PBL “Challenges” designed to scaffold the development of students’ problem solving and critical thinking skills. In this paper, we present the results of a pilot study conducted to examine student reactions to the PBL Challenges in photonics technician education. During the fall 2012 semester, students (n=12) in two associate degree level photonics courses engaged in PBL using the PBL Challenges. Qualitative and quantitative methods were used to assess student motivation, self-efficacy, critical thinking, metacognitive self-regulation, and peer learning using selected scales from the Motivated Strategies for Learning Questionnaire (MSLQ). Results showed positive gains in all variables. Follow-up focus group interviews yielded positive themes supporting the effectiveness of PBL in developing the knowledge, skills and attitudes of photonics technicians.

Keywords: Problem-based learning, photonics, collaboration, motivation, self-efficacy, critical thinking, metacognition, self-regulation, MSLQ.

1. INTRODUCTION

In the new global innovation economy, employers require creative, teamwork-oriented problem solvers capable of adapting to the ever-changing needs of business and industry. This is especially true in the field of photonics, in which rapid advances in technology require engineers and technicians to apply their knowledge and skills in solving problems in new and novel situations. A good problem solver approaches a problem, any problem, systematically and methodically, carefully considering all options before moving forward toward a solution. Good problem solvers are patient and methodical, breaking complex problems down into smaller, more manageable steps, and making reasoned decisions on how to approach each step. Good problem solvers use metacognitive strategies to manage the problem solving process by planning, monitoring, and evaluating their progress and strategies during problem solving, and adjusting their approach when necessary. Good problem solvers persist in the face of difficulty and have the confidence and motivation to seek alternative solutions. In short, good problem solvers are those who “know what to do when you don’t know what to do.”^{1,2,3,4,5}

But how do we teach students to be good problem solvers? Traditional instructor-centered approaches to technology education often do not provide students with the real-world problem solving experiences needed for students to develop the knowledge, skills, and attitudes needed to be good problem solvers. One instructional method that has been shown to

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be effective in helping students develop these skills is PBL. In PBL, students actively participate in their own learning by solving real-world problems in which the parameters are ill-defined and ambiguous. Unlike traditional lecture-based instruction in which students attend lectures and solve well-defined “end-of-chapter” homework problems, PBL is open-ended and contextualized, and student learning is driven by the problem itself. Research shows that PBL results in “deep” learning rather than “surface” learning, improves critical thinking and problem-solving skills, motivation for learning, and students’ ability to skillfully apply knowledge in new and novel situations.^{6,7,8,9}

With PBL, students learn both content and problem-solving ability by engaging in a systematic and reflective process that begins with *problem analysis*, in which small teams of students work collaboratively to properly define and frame the problem, identifying what is known, what needs to be learned, situational constraints and assumptions that might apply, and other pertinent problem features required to formulate a solution. Once the problem has been properly framed, students engage in self-directed learning in which they set specific learning goals and conduct independent research to acquire the knowledge, skills and resources needed to solve the problem. This is followed by brainstorming potential solution ideas with team members, where newly acquired information is synthesized and forged into possible solutions. The final stage is solution testing, where students develop strategies to test and validate their solutions⁸.

2. THE PBL CHALLENGES

In order to facilitate the use of PBL in photonics technology education, the *PBL Projects* of New England Board of Higher Education (NEBHE) has created a comprehensive series of online multimedia PBL Challenges through funding by the National Science Foundation Advanced Technology Education (NSF-ATE) program. The PBL Challenges are self-contained multimedia instructional modules designed to develop students’ problem solving and technical skills in the areas of photonics and sustainable technologies. Developed in partnership with industry partners, university researchers and other organizations, the PBL Challenges present students with authentic real-world problems captured and brought to life in a multimedia format designed to emulate the real-world context in which the problems were encountered and solved.

Each PBL Challenge contains five main sections:

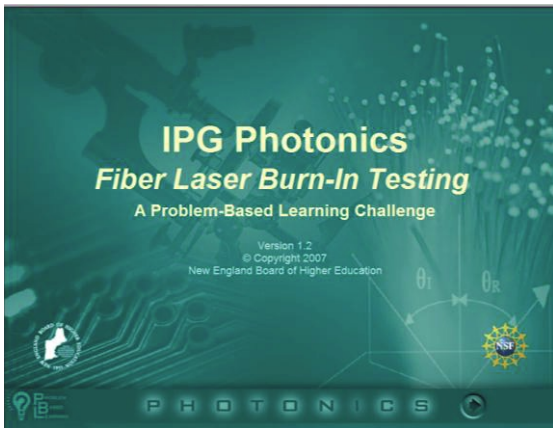
1. Introduction - An overview of the particular topic to be explored
2. Organization Overview - An overview of the organization that solved the problem
3. Problem Statement - A re-enactment of the situation and context in which the problem was originally encountered by the actual team of people who solved it
4. Problem Discussion - A re-enactment of the brainstorming session conducted by the team designed to model good problem solving skills and to provide students with additional hints
5. Problem Solution - A detailed description of the organization’s solution to the problem

The Problem Discussion and Problem Solution sections are password protected to allow instructors to control the flow of information and pace of instruction. Each of the five main sections contains additional information and resources (i.e., scripts, websites, spec sheets, etc.) designed to guide the student through the problem solving process. The PBL Challenges are designed to be implemented using three levels of structure ranging from highly structured (instructor led) to guided (instructor guided) to open-ended (instructor as consultant) representing increasing levels of autonomy to acclimate students to the PBL process and scaffold the development of their problem solving skills. The main sections of the PBL Challenges are shown in Figure 1.

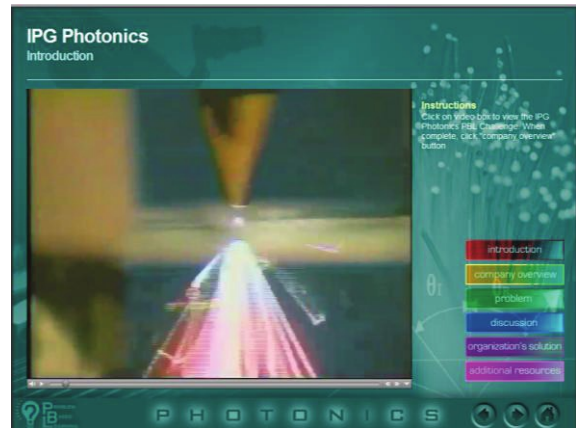
One unique feature of the PBL Challenges is the “Problem Solvers Toolbox.” The Problem Solvers Toolbox contains a tool called “The Whiteboards,” which guide students through a systematic four-phase problem solving process in which students respond to a series of specific questions posted on a mock whiteboard graphic. The Whiteboards help students capture and document their thoughts, ideas, and learning strategies during each stage of the problem solving process – a form of formative self-assessment. The four Whiteboards are shown in Figure 2:

1. Problem Analysis – Identifying what is known, what needs to be learned, and any problem constraints and assumptions to help students properly frame the problem
2. Independent Research – Setting specific learning goals, identifying necessary resources, assigning team member responsibilities, and developing a timeline for achieving learning goals

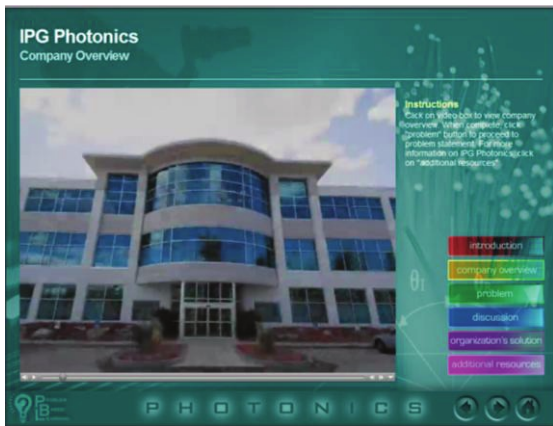
3. Brainstorming – Collaboratively generating and evaluating ideas and alternative solutions best suited for addressing the problem
4. Solution Testing – Developing a viable plan to validate the solution based on specific performance criteria



(a)



(b)



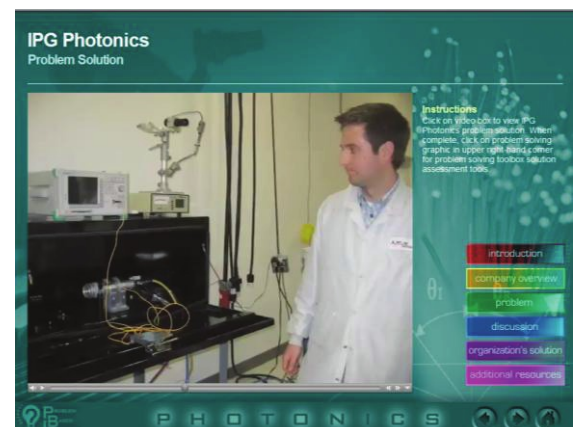
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(d)

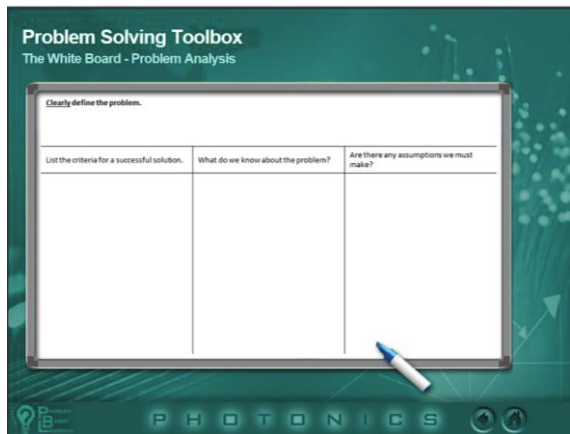


(e)

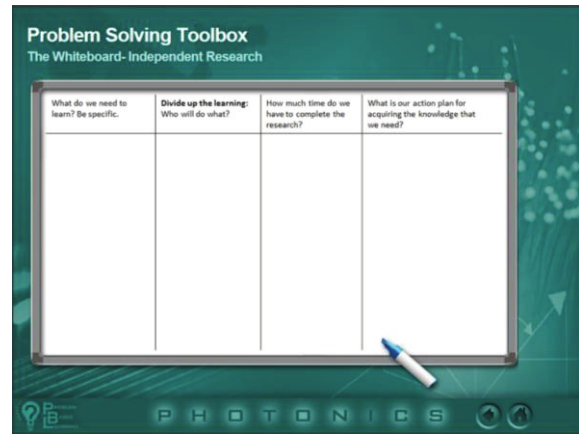


(f)

Figure 1. Main PBL Challenge Sections (a) Problem Analysis Whiteboard, (b) Independent Research Whiteboard, (3) Brainstorming Whiteboard, (4) Solution Testing Whiteboard



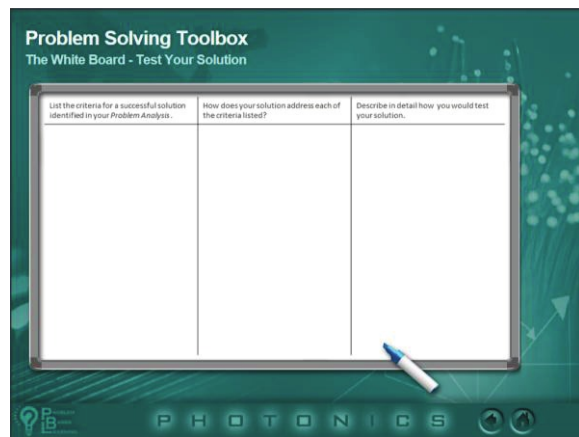
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Figure 2. (a) Problem Analysis Whiteboard, (b) Independent Research Whiteboard, (3) Brainstorming Whiteboard, (4) Solution Testing Whiteboard

Teacher resources including tutorials, assessment tools, and alignment with national science, math and technological literacy standards, a “How To” video, and a series of implementation case studies are incorporated into each PBL Challenge as well. To date, 14 PBL Challenges have been developed in partnership with industry and university partners with an additional six PBL Challenges in advanced manufacturing technology currently under development (to be completed by 201 and are available online at <http://www.pblprojects.org> to educators at no charge.

3. STUDENT REACTIONS TO PBL

The knowledge, skills and attitudes that students bring the classroom are important factors related to successful learning outcomes. This is especially true in PBL, where students accustomed to traditional instructor-centered education are thrust into a new and ambiguous learning environment in which the responsibility for learning is placed squarely on the shoulders of the student. In order for students to become effective problem solvers, they need to develop and internalize the problem solving and critical thinking skills needed to systematically dissect, analyze, and formulate coherent and viable strategies for solving problem. They also require the motivation and confidence to persist in the face of difficulty and seek alternative solutions, and the metacognitive ability to manage the problem solving process by planning, monitoring, and evaluating their learning strategy and adjusting their approach when necessary.

In this study, we examined the reactions of photonics technology students enrolled in a two associate degree-level courses in which students engaged in three PBL activities over the course of one semester. Five variables were examined; motivation, self-efficacy, critical thinking, metacognitive self-regulation, and peer learning. *Motivation* refers

to the amount of effort a student is willing to commit to a particular learning activity and can vary depending on the value that a student places on the activity. Students who engage in a learning activity out of personal interest in the topic (i.e., learning for learning sake) are said to be intrinsically motivated or mastery oriented. In contrast, students who engage in a learning activity for external rewards such as a good grade or promotion are said to be externally motivated or goal oriented. Research shows that while both motivational orientations are important for successful learning outcomes, students who are intrinsically motivated are more likely to engage in “deep learning” and persist in the face of difficulty¹⁰. In this study, we defined motivation using two constructs: (1) intrinsic goal orientation – the extent to which students are intrinsically motivated to engage in PBL activities for personal gain, and (2) extrinsic goal orientation – the extent to which students are motivated to engage in PBL activities for external rewards (i.e., grade).

Self-efficacy refers to a student’s confidence in his or her ability to be successful in a particular learning endeavor. Research shows that self-efficacy is an important factor related to positive learning outcomes and can moderate the amount of effort learners put forth in achieving a specific learning objectives¹¹. In this study, we defined self-efficacy as students’ confidence in their ability to engage in real-world problem solving.

Critical thinking refers to the degree to which students are able to apply previous knowledge to new situations in order to solve problems, reach decisions, or make critical evaluations with respect to performance standards¹². In order for students to develop critical thinking skills, they must be provided with authentic learning experiences that stimulate their interest and a supportive learning environment that allows for open and meaningful discussions and alternative viewpoints. Accordingly, proponents claim that PBL is ideally suited for improving students’ problem-solving and critical thinking abilities. Research shows that PBL can promote the development of students’ critical thinking skills^{13,14}, increase transfer and application of knowledge^{15,16}, and is effective in promoting higher-order thinking^{17,18}. In this study, we defined critical thinking as students’ ability to skillfully apply technical knowledge and problem solving strategies in solving real-world problems presented in the PBL Challenges.

Metacognition refers to the awareness, knowledge, and control of cognition, or in more simple terms, “thinking about thinking.”¹⁹ Metacognition is often expressed in terms of two constructs: Metacognitive knowledge and metacognitive self-regulation. Metacognitive knowledge includes three components: declarative knowledge refers to one’s knowledge of understanding of the specific requirements of the task at hand and of specific learning strategies; procedural knowledge involves knowing how to use a particular learning strategy; and conditional knowledge, knowing under what circumstances it is appropriate to use that strategy. Metacognitive self-regulation involves three primary components: planning, monitoring and evaluating. Planning involves activities such as setting learning goals, identifying resources, establishing timelines, and developing strategies for acquiring the desired knowledge. Monitoring involves tracking comprehension and understanding as one reconciles and integrates current information with prior knowledge. Evaluating involves the assessment and adjustment of learning strategies and cognitive activities after a learning episode.²⁰ Research shows that metacognitive self-regulation can improve learning outcomes by assisting learners in continuously monitoring and correcting their understanding and comprehension as they engage in a learning task, and is a key factor linked to students’ ability to transfer knowledge and skills to new situations.^{20, 21,22} Accordingly, researchers agree that PBL, in which students learn to take responsibility for their own learning, is ideally suited for supporting the development of metacognitive self-regulation.^{21,23,24} Moreover, researchers maintain that metacognition is an essential component of critical thinking arguing that monitoring the quality of one’s learning and thought process makes it more likely that one will engage in high-quality (critical) thinking.^{19,20,25} In this study, we defined metacognitive self-regulation as students’ ability to apply specific learning strategies to plan, monitor, and evaluate their learning while solving real-world problems presented in the STEM PBL Challenges.

One of the cornerstones of PBL is *collaborative or peer learning*. In collaborative learning, students work together in small teams toward a common goal and are active participants in each other’s learning, helping each other to be successful. Researchers maintain that the active exchange of ideas among team members in collaborative learning increases interest among participants and promotes critical thinking.³² Students who work collaboratively also exhibit higher levels of thought and retain information longer than students who work independently.³³ Collaborative learning provides students the opportunity to engage in discussion, take responsibility for their own learning, and thus become critical thinkers.³⁴ In this study, we define collaborative or peer learning as students’ effective use of other students to help their learning.²⁹

4. METHOD

This study was conducted during the fall 2012 semester as an observational case study.^{26,27, 28} Quantitative and qualitative measures were applied to answer the research question, “How and in what ways does engagement with the PBL Challenges affect photonics technology students’ motivation, self-efficacy, critical thinking skills, metacognitive self-regulation, and peer learning needed to successfully apply problem solving strategies in solving real-world photonics problems?”

A total of 12 volunteer (9 male: 3 female) first and second year photonics technology students from two east coast community colleges enrolled in two 3-credit one-semester photonics technology courses participated in the study. On average, study participants were between 25-35 years old and none had ever taken a course in which PBL methods were used.

Over the 16-week semester, each class was divided into teams of 3-4 students tasked with completing three PBL Challenges. The first PBL Challenge was implemented in a “structured” or cases study mode (~ 2 weeks) in which the instructor worked closely each team to tutor and guide in the PBL process. The second PBL Challenge was implemented in a “guided” mode (~ 3-weeks) in which the instructor played the role of facilitator and students were given more autonomy in an effort to help them develop self-directed learning skills. The third and final PBL Challenge was implemented in an open-ended mode (~ 4 weeks) in which teams had complete autonomy to work through the problem solving process to develop their own solutions. During the third Challenge, the instructor played the role of consultant, providing guidance on an “as needed” basis. At the end of each PBL Challenge, each team presented their solution to the class and discussed the process they employed in solving the problem. A class discussion followed in which students compared and contrasted their solutions with the PBL Challenge solution.

Two measures were used to answer the research question:

- Motivated Strategies for Learning Questionnaire (MSLQ) - The MSLQ is a widely used and validated 81-question Likert-scaled self-report instrument designed to assess college students’ motivation and use of learning strategies²⁹. Motivation (intrinsic and extrinsic), self-efficacy, critical thinking, metacognitive self-regulation, and peer learning were measured using selected subscales from the MSLQ. Chronbac’s alpha for each variable are reported as intrinsic motivation (4 items; $\alpha=.74$), extrinsic motivation (6 items; $\alpha=.62$), self-efficacy (8 items; $\alpha=.93$), critical thinking (5 items; $\alpha=.80$), metacognitive self-regulation (12 items; $\alpha=.79$), and peer learning (3 items; $\alpha=.76$).
- Semi-Structures Interviews – An independent evaluator conducted two focus group interviews at the end of the fall semester using a semi-structured protocol. Transcripts from the focus group interviews were coded and themed to supplement MSLQ data and to provide additional insight into issues related to students’ reactions to the PBL Challenges with regard to their problem solving ability.

Students were invited to participate in the study by volunteering to complete a pre-post online survey (MSLQ) and participate in a focus group interview at the end of the fall 2012 semester. Mean values were computed for each variable from the MSLQ subscales and data were screened for outliers and normality. Paired t-tests were conducted to measure changes in mean scores for each variable. Effect sizes³⁰ (Cohen’s d) were calculated using t-scores and sample size to quantify the effect of PBL instruction on the variables in question. To encourage student participation, a cash gift card was given to those students who completed the requirements of the study. The MSLQ was administered using SurveyMonkey® and analyses conducted using SPSS v.19. Researchers were available to respond to any questions or concerns via e-mail and telephone.

5. RESULTS

5.1 Motivation

Results of paired t-tests performed on the MSLQ motivation subscales data showed an increase in intrinsic motivation with a small to medium effect size ($t = .757$, $p = 0.466$; Cohen’s $d = 0.309$), and an increase in extrinsic motivation with a medium to large effect size ($t = 1.773$, $p = 0.107$; Cohen’s $d = 0.724$). Paired t-test results were corroborated through thematic analysis of student interview data. Students were asked “*Did the PBL Challenges increase or decrease your motivation to engage in your coursework as compared to other non-PBL courses?*” Supporting comments included:

- *“The way it was taught made me want to come to class. It made me excited to come to class, do work and realize that this could be fun and that's really exciting for me.”*
- *“I knew that every time I came in and we were doing something like this I would be learning something and it was going to be like- it was going to be new and exciting.”*
- *“I think for me, experience is the key word in this. It made the whole classroom environment feel like I was actively involved in something rather than being just a spectator.”*
- *“It felt less like a class I had to go and like a class I actually wanted to go to because it was fun and I was still learning.”*
- *“Your confidence in the process was definitely a motivational tool and the fact that the previous PBL projects were fairly successful, definitely increased motivation.”*
- *“I think just being here working together kind of pressures you to work harder and get more engaged because you have other people depending on you. So that's a motivating factor.”*
- *“I'd say my motivation increased because people depend on you and you know your project is like an issue you have to solve. Group collaboration is always key.”*
- *“I think my motivation definitely increased... If you go into a project that you really don't know anything about and you can successfully complete it. That does volumes for you.”*

Results showed that overall, student motivation for learning improved as a result of engaging in PBL. Students commented that they were much more motivated to learn using PBL methods as opposed to traditional lecture-based methods because they were actively engaged in problems that were meaningful and representative of what they would be required to do once they are in the field. Students also commented that the collaborative nature of PBL was a motivating factor because of the shared responsibility among team members. Moreover, students reported that the confidence gained in their problem solving ability further motivated them to engage in additional PBL activities.

Results from analyses of the MSLQ data suggests that while students' personal interest in learning course content increased as a result of engaging in PBL, they may have been more motivated to engage in PBL by external rewards (i.e., grades). Given that the students in the study were all enrolled in a required course in their major, they may have been more focused initially on successfully completing the course requirements in order to graduate than “learning for learning” sake. Analysis of focus group interview data did, however, show that intrinsic motivation increased with time and experience with the PBL Challenges. One explanation may be that because the photonics technology students had only completed three STEM PBL Challenges, they may not have completely internalized the problem-solving process and were still acclimating to PBL. In a previous study⁸, researchers found that engineering technology students who had completed four or more PBL Challenges showed a greater increase in intrinsic motivation as measured by the MSLQ than students who had completed just two PBL Challenges, and actually exhibited a decrease in external motivation, suggesting that over time and with more PBL experience, external motivation could be internalized, resulting in a transition from a goal orientation to a mastery orientation.

5.2 Self-efficacy

Results of paired t-tests on the self-efficacy subscale of the MSLQ showed a small increase ($t = .372$, $p = 0.717$; Cohen's $d = 0.152$) with a small effect size. Paired t-test results were corroborated through analysis of student interview data in which students were asked “Do you feel more confident in your ability to solve real world problems as a result of engaging with the PBL Challenges?” Supporting comments included:

- *“I feel a lot more confident based on the problem-based learning. Before PBL, when presented with a problem I would just try to solve it. Now I understand that I never really understood what the problem was, how to break it down, how to think it through...”*
- *“Now I have the confidence that if I follow this procedure, I'm going to have dotted all my 'I's and crossed all my 'T's and I'm not going to feel like somebody's going to say 'she don't got it, she don't know what she's doing – go back and do it again.”*

- *"I actually felt like the criticism we received while we were doing our presentation was one of the most valuable aspects of the whole experience. While I felt like I was really prepared, maybe I wasn't. But I think the first project was more like that than the second project. We got a little better, and I think we got better as time went on, and the last one we went up there and we felt like 'Hey! We nailed this thing.'"*
- *"I feel the confidence in my ability and the confidence in the process grew seeing the process vetted time and time again... It gives you that level of confidence to say, 'Yes I can do this,' or, 'I'd like to do that. Next time I would like to try that, or do things differently.' And so it's a self-correcting process you really do start perfecting."*
- *"By the time you get to the 3rd project you feel confident and you're looking forward to the next one or you're thinking about how you can do things better.... Now you're thinking, 'Wow, I could really do it better next time, pay more attention to the details' and take that creative criticism that you got and grow yourself - actually hone your craft."*
- *"There was definitely a bit of a learning curve for me, once I learned to trust the procedure, I realized that after the 3rd project this procedure really works well and gets you to your goal very quickly and efficiently."*

Overall, these results show that students were more confident in their ability to solve real-world problems as a result of completing the STEM PBL Challenges. Students commented that the more PBL assignments they completed, the more confident they became in the problem solving process because they gained confidence that the process they had learned would yield positive results. Students also reported that the more confident they became in their problem solving ability, the more motivated they became to engage in additional PBL activities. Moreover, students commented that as their confidence in their problem solving ability grew, the more confident they became in questioning their own learning and understanding, and were more willing to take corrective action in the future, suggesting a positive relationship between self-efficacy and metacognitive ability.

These results are consistent Bandura¹¹ who defined self-efficacy as the degree to which an individual is confident that he or she can perform a specific task or accomplish a specific goal. Bandura maintained that self-efficacy is extremely important for self-regulated learning because it affects the extent to which learners engage and persist at challenging tasks. In addition, students with higher self-efficacy are more likely to engage in a difficult task and more likely to persist at a task even in the face of initial failures compared to low-efficacy students. These results are also reflective of Bandura's social cognitive theory, which contends that learning is governed by a variety of interacting cognitive, metacognitive, and motivational components whereby learning progresses through a continuum ranging from observation and imitation in which learners rely on modeling behavior and through external feedback and guidance, to self-controlled and self regulated learning, in which students rely increasingly on internal self-regulatory skills and are capable of constructing internal standards for gauging acceptable performance. In short, as self efficacy beliefs increase, students are more likely to activate their repertoire of cognitive, metacognitive and motivational strategies required to self-regulate their learning.

5.3 Metacognitive self-regulation

Results of paired t-tests on the metacognitive self-regulation subscale of the MSLQ showed a substantial increase ($t = 1.968$, $p = 0.085$; Cohen's $d = 0.803$) representing a large effect size. Thematic analysis of interview data suggests that overall, students' metacognitive self-regulation improved as a result of completing the PBL Challenges. Paired t-test results were corroborated through analysis of student interview data. Supporting comments included:

- *"I think for me one of the biggest things was the allowance to make mistakes. You learn a lot more from your mistakes..."*
- *"I learned to trust in the process - if I complete each step in the process I will come out with a reasonable answer. Yes, I skipped this part or maybe I should have paid more attention to this part, but you were able to do a self analysis and self correction and improve the quality of your work each time you do it."*
- *"I think our first project we spent a long, long time on the very preliminary processes of assigning task. I think the next time we spent maybe half an hour or 45 minutes because we knew what the process was so we had confidence in it. We knew what research had to get done. You do this, this, this, we'll come back on this day and move on to the next stage."*

- *“You clearly realize while working where your strengths are and your weaknesses lie. And for me, having it pointed out where my weaknesses lie encourages me or motivates me to work harder in the areas I know I need improvement.”*
- *“For me it was just repetition...the process It was just going back to breaking down the problem, white boards, asking the right questions, and making sure you carefully think through the problem on paper before you start getting your hands dirty.”*
- *“And like I said, the trust in the process that if I complete each step in the process I will come out with a reasonable answer. Yes, I skipped this part or maybe I should have paid more attention to this part, but you were able to do a self-analysis and self-correction and improve your quality of your output each time you do it so that brings on confidence.”*
- *“Well it also put a lot of focus on time management. Time management is one of the largest factors in the whole set up because we only met once a week. Occasionally there would be two, maybe three weeks at a time before there would be a deadline. So you really need to manage your time, because if you don’t, you’re not going to be successful.”*
- *“It’s like there was a dead line, but it was two or three weeks away. So in between the inception of the project and the final the team had to manage that time in between...”*

Overall, results show that students’ metacognitive self regulation skills were improved as a result of engaging in PBL. Specifically, students commented that PBL helped them develop better time management skills as a result of planning for independent research (i.e., goal setting). Students commented that working in teams provided an increased sense of responsibility resulting from having other team members depend on them to get their share of the work done. Students also stated that they appreciated being able to learn from mistakes and being provided with constructive criticism and an opportunity for corrective action as opposed to being penalized as in traditional lecture-based classroom.

Student comments also provided evidence of improved metacognitive self-regulation through their responses in which they described the problem solving process in terms of reflecting on their current understanding of the problem and its parameters, identifying knowledge gaps, and planning strategies for implementing and testing their solution – all key attributes of metacognitive self-regulation. As students collaboratively engaged in problem-solving through the use of the whiteboards, they were able to reflect upon and verbalize their current state of understanding, their thought processes, and problem solving strategies. Research shows that verbalizing the thought process while engaging in problem solving improves metacognition, an essential component of effective problem solving²¹. Upon completion of each PBL Challenge, students were required to complete a reflective journal in which they provided a detailed summary and critical analysis of the problem-solving process employed in solving the PBL Challenge. Researchers maintain that this final reflective exercise is essential in the development of effective metacognitive and problem-solving skills³². Clearly, results suggest that as students collaboratively engaged in the structured and recursive problem solving process facilitated by the PBL Challenge whiteboards and critically reflected on their problem solving process via the final reflective journal, they improved their metacognitive self-regulation skills necessary to plan, monitor and evaluate their learning.

5.4 Critical thinking

Results of paired t-tests performed on the critical thinking subscale of the MSLQ showed a substantial increase ($t = 1.423$, $p = 0.185$; Cohen’s $d = 0.893$) in critical thinking with a large effect size. These results suggest that overall, students’ critical thinking skills improved as a result of completing the PBL Challenges. Paired t-test results were corroborated through analysis of student interview data. Supporting comments included:

- *“The PBL approach was - it was very structured and it really got us practicing the process of problem solving rather than just asking the question and saying ‘what’s the answer’...?”*
- *“I found myself whiteboarding different problems in my life..., just looking at the whiteboards and starting to fill in the sections really helped me to understand subject matter that I was not really familiar with. So it teaches you what to do when you don’t know what to do”.*

- *“It clearly helped me to solve a problem, to break it into different pieces and pull the trigger on which aspects you know. Then the one you don’t know you can think about and come to a conclusion after you’re done. It really helped me”*
- *“The PBL did affect me because I tend to jump from what I know first. So I would skip the beginning steps of the process and go straight for what I know, which is a knee jerk reaction. We all do that; we want to go to the comfortable part, the things we think we can solve. But to go to that uncomfortable part, the thing we are unfamiliar with, the whiteboarding, answering all those questions, really forces you to look at the problem in depth, and it’s a training tool to keep you on task. Once I realize what it was doing, I said, ‘this is great.’”*
- *“I think it's more practical like you actually like know what you are supposed to do in a real world situation”*
- *“I think we all learned a lot from the assignment. Speaking for myself I learned a lot about the problem solving process.”*
- *“To actually put pen to paper and chug through that process, at first that seemed like, ‘oh my gosh another whiteboard,’ but then I realized, this is really helping me, because in the end, you have all the tools you need right in front of you and you know exactly where to go.”*

As described earlier, critical thinking involves the degree to which students apply previous knowledge to new situations in order to solve problems, reach decisions, or make critical evaluations with respect to performance standards¹². It is clear from the student comments that engagement with the STEM PBL Challenges provided a valuable learning experience in which students were able to draw from and synthesize prior knowledge acquired in other classes, from their own research and that of their peers, and were able to converge on a problem solution that addressed specific performance criteria – consistent with the definition for critical thinking.

5.5 Peer learning

Results of paired t-tests performed on the peer learning subscale of the MSLQ showed a small increase ($t = 0.662$, $p = 0.525$; Cohen’s $d = 0.296$) in peer learning with a small effect size. This results shows that overall, students’ assessment and/or perception of the value of collaborative learning improved as a result of completing the PBL Challenges. Paired t-test results were corroborated through analysis of student interview data. Supporting comments included:

- *“It was the group collaboration that really steered, at least in my group, toward the final answer, that I don’t think either me or my partner would have been able to accomplish without collaborating and coming together with our ideas.”*
- *“The biggest thing is the life experiences that everybody gains, even me, through working with groups and the diversity of people. Not just ages- different backgrounds, different upbringings so on and so forth. We all came from different places and as I said before, when we bring our own life experiences to these situations, it's helpful. It's very helpful.”*
- *“You could look at it [collaboration] as a double edged sword, because just as a weak team member could hurt your overall performance as a group, it can also strengthen the members who are in the group who are willing to pull a little more weight.”*
- *“You can either look at it [collaboration] as a negative or turn it into a positive and invest some time in the team member and teach them or help them to meet the mark. And that’s a personal choice that you have to decide if you’re going to do that or not. But that’s just a reality out in the real world. People get sick, things happen.”*
- *“Some people will say ‘Oh this is great’ and others ‘Oh this isn’t so great.’ But I think it is part of the team dynamic, and if you ever think you’ll get a real world that doesn’t work like that I think you’re fooling yourself. I think it works as a plus and negative but at the end you’ve got to take it as a plus because you’re learning to work with all dynamics.”*

Analysis of student interview data provided important insight into the value of collaborative learning and teamwork in solving complex real-world problems. Students commented that they enjoyed the opportunity to work in teams because it allowed for different perspectives to be shared, and in particular, the value of drawing from the collective experience of the team. As is sometimes the case, one of the drawbacks of collaborative learning is that some students contribute

more to the team effort than others. To help avoid this situation, at the beginning of each PBL activity students were given a teamwork assessment form in which they would be required to rate their team members in four categories of performance using a 5-point Likert scale. The intent of the teamwork assessment was to prevent students from “slacking” in their responsibilities, which proved to be fairly effective. Interestingly, students cited both positive and negative aspects of working in teams. While some students were reported to contribute less than others to the team effort, higher performing students viewed this as an opportunity to improve their own learning by compensating for that shortcomings of the lower performing students. They also viewed the non-performance of some of their teammates as an opportunity to help a struggling classmate improve his/her skills. Overall, students viewed the collaborative nature of PBL as a valuable opportunity to experience the ups and downs of team dynamics that they would encounter in the real world.

6. CONCLUSION

In this paper, we presented the results of a study conducted to examine student reactions to PBL in photonics technology education. The purpose of the study was to ascertain whether PBL represents a viable alternative to traditional lecture-based methods in preparing photonics technicians with the problem solving and critical thinking skills needed to adapt to the rapidly changing demands of the 21st century workplace. During the fall 2012 semester, 12 photonics technology students enrolled in two associate degree level courses at two east coast community colleges completed three photonics-related PBL Challenges over the course of a 16-week semester. Qualitative and quantitative methods were used to assess students’ motivation, self-efficacy, critical thinking, metacognitive self-regulation, and peer learning using selected scales from the MSLQ. Data were corroborated through post-course focus group interviews with students conducted by an independent evaluator. Analysis of pre-post MSLQ data showed gains in intrinsic and extrinsic motivation, self-efficacy, critical thinking, metacognitive self-regulation, and peer learning. The results of the study showed that overall, photonics technology students reacted positively to the PBL method of instruction. Students reported being motivated by the real-world nature of the problems presented in the PBL Challenges and were excited to come to class and engage in additional PBL Challenges. Results also showed that with increased experience with PBL, students developed the confidence and critical thinking skills needed to solve ill-structured problems and the metacognitive ability to plan, monitor, and evaluate their own learning and performance – skills deemed critical for lifelong learning. Finally, results showed that students learned to work collaboratively and productively in teams and were able to draw upon the collective knowledge and experience of team members to effectively converge on problem solutions. In addition, learning to deal effectively with underperforming team mates by viewing the issue as a learning opportunity was an unexpected but positive outcome. While the results are encouraging, given the small sample size, lack of a control group, and other threats to internal validity, the generalizability of this study is limited to the study population. Future studies should include a larger sample size and an experimental or quasi-experimental design to improve internal validity and generalizability.

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