IJPBL http:// ijpbl.org

Interdisciplinary Journal of Problem-Based Learning

Volume 12 | Issue 2 Article 7

Published online: 9-10-2018

Exploring Problem-Based Learning for Middle School Design and Engineering Education in Digital Fabrication Laboratories

Monica M. Chan
Teachers College, Columbia University, mmc2265@tc.columbia.edu

Paulo Blikstein
Stanford Graduate School of Education, paulob@stanford.edu

IJPBL is Published in Open Access Format through the Generous Support of the Teaching Academy at Purdue University, the School of Education at Indiana University, and the Jeannine Rainbolt College of Education at the University of Oklahoma.

Recommended Citation

Chan, M. M. , & Blikstein, P. (2018). Exploring Problem-Based Learning for Middle School Design and Engineering Education in Digital Fabrication Laboratories. *Interdisciplinary Journal of Problem-Based Learning, 12*(2).
Available at: https://doi.org/10.7771/1541-5015.1746

Exploring Problem-Based Learning for Middle School Design and Engineering Education in Digital Fabrication Laboratories

Cover Page Footnote

A warm thank you to the Honors Thesis program at the Stanford Graduate School of Education for its guidance throughout this research project, and Stanford's Undergraduate Advising & Research (UAR) Grant that provided funding for this research project.

The Interdisciplinary Journal of
Problem-based Learning

Special Issue: Tinkering in Technology-Rich Design Contexts

Exploring Problem-Based Learning for Middle School Design and Engineering Education in Digital Fabrication Laboratories

Monica M. Chan (Teachers College, Columbia University) and

Paulo Blikstein (Stanford University Graduate School of Education)

Abstract

This is a research study of design and engineering classes that use a problem-based learning (PBL) approach in digital fabrication makerspaces in two middle schools. In these studies, teachers employ a PBL approach and provide an ill-structured problem scenario to facilitate design and engineering lessons in the FabLab (fabrication laboratory). Students in each school tackled different challenges that they defined for themselves in groups. This study provides examples of student-student interactions separated into key themes—defining specifications with teammates, personal exploration, and communication about discoveries. This study also provides examples of teacher-student interactions, and themes include demonstrations with tangible objects, discussing prototype failure, and managing behavioral issues. The purpose of this study is to provide insights about PBL in a nontraditional, technology-rich FabLab environment.

Keywords: problem-based learning, digital fabrication, engineering education, design education, middle school

In the 21st century, there have been shifts toward incorporating inductive pedagogical approaches in engineering education not only in higher education where it is traditionally found, but also at K–12 levels. In fact, the latest release of the Next Generation Science Standards (NGSS) for K–12 STEM education has demonstrated that there is a need for implementation of engineering and design education at K–12 levels. This paper will focus on problem-based learning (PBL) at the middle school level for engineering and design. PBL is an inductive pedagogical approach that emphasizes learning via meaningful tasks and open-ended problems (Hmelo-Silver, 2004). PBL approaches are not new, having foundations in the early 20th century, when Kilpatrick (1918, 1921) and Dewey (1938) both highlighted the importance of experiential learning. Such inductive pedagogical approaches are "promotive of the problem-solving skills and attitudes that most instructors would say they desire for their students" (Prince & Felder, 2006) and encompass authentic problems that enhance students' understanding of engineering concepts (Prince & Vigeant, 2006). This paper focuses on PBL in middle schools' digital fabrication laboratories (FabLabs), which is a technology-rich and technology-mediated, nontraditional learning environment. To clarify, the middle school FabLabs used in this study may not have been directly registered with the Fab Foundation, but have been modeled to emulate FabLabs that are part of the Fab Foundation's umbrella, and the coordinators that ran these schools' FabLabs were members of the FabLearn Fellows.

Bringing the maker movement into K–12 education has been a recent phenomenon. A rapidly developing type of makerspace is the Fabrication Laboratory, more commonly known as FabLab for short. Neil Gershenfeld, a professor at MIT, invented the FabLab, which consists of a set of digital fabrication and prototyping tools such as a laser cutter, a vinyl cutter, CNC routers, and 3D printers (Davee, Regalla, & Chang, 2015). Digital fabrication is simply defined as "translating a digital design into a physical object" (Bull, Gerald, & Gibson, 2009). According to Gershenfeld, digital fabrication will "allow

http://dx.doi.org/10.7771/1541-5015.1746

individuals to design and produce tangible objects on demand, wherever and whenever they need them" (Gershenfeld, 2012).

In the past five years, there has been a growing community of K–12 educators who have started makerspaces in schools. More specifically, a number of schools have also established FabLabs, as these schools are able to have more high-tech digital fabrication devices and trained teachers on campus. Many educators use PBL to drive how they construct and deliver curricula to students in this nontraditional learning space.

Although PBL has existed in pedagogy for years, PBL applied to a technology-rich learning environment such as a FabLab is relatively new. Still uncertain and unknown is the extent to which strong problem-solving and engineering skills can be developed in FabLabs. This raises questions as to how students collaborate with one another in this high-tech environment, and how teachers and students interact in these spaces under PBL. This research project explores how PBL works in a FabLab environment with a focus on middle school engineering education, and uses case studies from two middle schools that have a FabLab on campus. In this study, we investigate how FabLabs in schools function as learning environments that harness PBL, and how PBL in FabLabs affect collaboration among students and teachers.

This gives rise to the following guiding research questions:

1. How did the FabLab environment and digital fabrication tools affect how students collaborated and communicated their ideas with one another in a PBL approach?
2. How did a PBL approach in each of the FabLab learning environments affect teacher-student interaction?

Literature Review

Constructivism and Constructionism

Dewey, Papert, and Freire all highlighted experiential education as a major component of holistic learning. Dewey proposed the idea that education should be more experiential and connected to the real world (Dewey, 1902; Freudenthal, 1973; Froebel & Hailmann, 1901; Montessori, 1965; Von Glasersfeld, 1984). Freire (1972) introduced the idea of "culturally meaningful curriculum construction," where designers are inspired by local culture toward creating "generative themes" with local members who are familiar with the culture. With motivations similar to Freire's, Papert, one of the pioneers of artificial intelligence, pioneered the use of digital technologies in education.

Building on Piaget's theory of constructivism that was based on discovering by using one's senses (Piaget, 1980; Wadsworth, 1996) and on Vygotsky's theory of social constructivism that emphasized the significance of socializing and collaborating among learners (Hodson & Hodson, 1998; Jamarillo, 1996), Papert founded the theory of constructionism. Papert claims that the construction of knowledge happens incredibly well when students build, make, and publicly share objects. A child will "build (his/her) own intellectual structures with materials drawn from the surrounding culture" (Papert, 1980; Papert & Harel, 1991). Then, this enables the child to create "hierarchies of knowledge" and develop stronger intellectual skills (Papert, 1980).

Brennan (2015) builds on Papert's theory of constructionism and defines four essential aspects to designing constructionist learning environments—designing, personalizing, sharing, and reflecting—all of which are illustrated with complementary perspectives from other scholars in this field. For designing, constructionist approaches value learning through design activities, critical thinking, and creativity, and engage learners in iterative thinking (Brennan, 2015; Papert & Harel, 1991). Berland emphasizes that constructionism is a "framework for action" (DiSessa & Cobb, 2004) that teaches people to express themselves via computation by using DiSessa's computational literacy construct (Berland, 2016, p. 198). Kafai and Burke (2014) have used the term *computational participation* to illustrate constructionist engagement with authentic, social, community-based perspectives. This notion of constructionism ties in closely with the maker movement and hence the development of FabLabs in schools.

For personalizing in a constructionist sense, the design of the learning experience should focus on multiple levels, such as the learner's cognitive and affective aspects. Turkle and Papert (1990) recognize both bricoleur and planner approaches in maker-oriented activities, in a planner-dominated culture. For sharing, Vygotsky's notion of the Zone of Proximal Development and theories of situated learning and communities of practice add to the discourse about expanding individual cognition by including others' expertise and abilities in increasing one's capabilities (Cole & Wertsch, 1996; Lave & Wenger, 1991). Finally, for reflecting, there is an emphasis on metacognition (Flavell, 1979), which is closely connected to the significance of learner agency in constructionism.

Problem-Based Learning

PBL is a student-centered approach that is widely used as a method of instruction in many schools and higher education institutions. PBL, which focuses on guiding students to build self-directed learning skills, is derived from seminal learning theories such as constructivism (Piaget) and constructionism (Papert) where the learners actively construct new knowledge based on their current knowledge (Awang & Ramly, 2008). PBL also helps students develop creative thinking, problem solving, and communication skills (Awang & Ramly, 2008; Major & Palmer, 2001).

PBL originated from medical education in the 1980s, when medical faculty came to realize that the process of patient diagnosis comes from a team effort that relies on inductive reasoning and expert knowledge from doctors in multiple domains (Barrows, 1996; Barrows & Tamblyn, 1980). This teaching discipline spread widely in the 1980s and 1990s to various medical schools, and now has entered other academic fields and K–12 education (Torp, 2002).

Savery (2015, p. 15) summarizes three important characteristics that clearly identify PBL from the various definitions scholars in the past two decades have provided:

1. The role of the tutor as a facilitator of learning;
2. The responsibilities of the learners to be self-directed and self-regulated in their learning;
3. The essential elements in the design of ill-structured instructional problems as the driving force for inquiry.

Savery also reminds us that PBL is challenging because it needs significant, thoughtful scaffolding to support students' development of problem-solving, self-regulation, and collaboration skills (Savery, 2015, p. 15).

During the process of PBL, students use prompts from a problem scenario to define their own learning objectives. There are usually four phases in a PBL learning cycle—problem presentation, problem investigation, problem solution, and process evaluation (Awang & Ramly, 2008). Typically, the students will have little prior knowledge about their problem scenario (Barrows, 2000). Then, they will discuss with their teammates how to plan a direction to work on the problem scenario based on their current and any newly acquired knowledge. PBL does not solely focus on problem solving, but also focuses on using appropriately ill-structured problems to drive students' learning. Due to the major component of group work, PBL can also be viewed as a small group teaching method that combines knowledge acquisition with creative higher-order problem-solving development (Awang & Ramly, 2008; Hmelo-Silver, 2004; Steinemann, 2003).

FabLabs

Martin (2015, p. 31) clearly states that there is no clear definition to what constitutes "making," since scholars have similar yet varied definitions of this particular term. Martin highlights the *maker mindset*, where qualities such as playful, growth-oriented, failure-positive, and collaborative are key (2015, p. 36). These are qualities that also coincide with the three essential characteristics of PBL, as listed earlier. Kuznetsov and Paulos (2010) conducted a large-scale study on DIY (do-it-yourself) communities, and emphasized that in the last decades, social computing, online sharing tools, and other collaboration and sharing technologies have led to a renewed interest and wider adoption of DIY cultures and practices. Over time, community and industry makerspaces grew, mostly for adults and technicians. Mota (2011) describes this as the "Democratization of Manufacturing," our second industrial revolution in the 21st century. She highlighted that access to personalized digital fabrication tools, such as the 3D printer and laser cutter, has increased significantly due to cheaper manufacturing costs and a surge in demand.

Posch and Fitzpatrick (2012) conducted an out-of-school 2-day workshop for middle school students to introduce them to the world of a FabLab in individual modules, mainly 2D and 3D fabrication, printed circuit board fabrication and assembly, and basic programming. Most of the learning results were positive. Posch and Fitzpatrick's conclusion was that introductory workshops are certainly not enough to satiate the demand of middle school students who want to learn more using digital fabrication, and that there should be more research in children's self-directed interaction with digital fabrication technologies and how makerspaces can support technology literacy and learning in children (Posch & Fitzpatrick, 2012). These scholars' research establishes the limited amount of research about digital fabrication at the middle school level.

Another academic viewpoint comes from Blikstein, who has also conducted research and written extensively about the potential of digital fabrication as an instructional technology, and attitudes toward having digital fabrication to teach STEM subjects (versus vocational education) in schools. The primary difference between Blikstein's and Posch and Fitzpatrick's articles is the idea of digital fabrication activities as "electives" or "extracurricular." Blikstein (2013) introduces the concept of having digital fabrication activities as part of the core curriculum in schools, in classes, to help students learn more actively.

Method

A case study approach was used to study two middle school FabLabs that are motivated by introducing engineering education to middle school students via the PBL approach.

The first research site is a charter school that has a FabLab where the FabLab director (head teacher) guided his sixth- and seventh-grade students through a three-month-long project that prompted them to identify a physical problem or inconvenience in their classroom's furniture and build a prototype to solve the problem. The second research site is a private school that has a FabLab where a science teacher guided her fifth- and sixth-grade students through a semester-long project that prompted them to explore famous 20th-century women's biographies and create a tangible museum exhibit for their peers by the end of the semester.

Site Selection

Two middle school sites that are equipped with an active FabLab on their campuses were chosen for this study. At both sites, a FabLab "classroom" typically consisted of one to two teachers with approximately 15 to 25 students. The research participants include the teachers of each middle school (research site) and their students in the design and engineering class. Most of their students were in sixth grade, while several were in fifth grade. The students were around 11 to 13 years old and came from nearly similar high socioeconomic backgrounds.

At both schools, FabLab classroom sessions were integrated into the students' school day. At the first school site, there was a designated FabLab director/teacher who taught the FabLab class separately from traditional mathematics and science classes. At the second school site, the FabLab teacher had the title of "science teacher" and "makerspace coordinator" and her class was called "science project work." Both teachers at both middle school sites worked in the FabLab space extensively. Both FabLabs were decently sized—they could fit 20 students and could accommodate technologies such as a laser cutter, 3D printer, and shelves of hand tools and craft materials. The furniture (tables and chairs) in both spaces could be easily moved around.

Data Collection

First, classroom observations were mostly passive. Students' collaboration methods with one another were examined passively, while they worked in the classroom in groups on their projects. Different forms of interaction between the teacher and students were observed too. To aid classroom observations, an observation checklist (see Appendix 1) had been prepared in advance, and makerspace and classroom activities were recorded using field notes and photographs. These classroom observations helped generate a context for how classes in makerspaces are organized and conducted. A total of nine makerspace classroom sessions were observed over the course of eight weeks; six sessions were from the charter school in the first case study and three sessions were from the private school in the second case study.

Additionally, semistructured interviews were conducted with each FabLab teacher about how they integrate PBL and various areas of STEM into making and designing in FabLabs. Each interview lasted no longer than an hour. Questions in the interview protocol have been included in Appendix 2. These interviews were conducted to gain a fuller understanding of the teachers' thought processes behind the curricula they designed for their FabLab classes, and their ideas and opinions about how to incorporate PBL into the FabLab.

Data Analysis

Since this was a largely qualitative research study, the photographs taken during classroom observations and field notes from the observations and interviews were reviewed during data analysis. Recurring themes were found in the observations and interviews, and these themes were categorized. Interrater reliability was not performed as this was an independent honors thesis project. Some focuses included instances of students working together on a particular challenge or task for the day, what tools they used when they worked together, examples of teachers interacting with students, and what tools (if any) they used or explored when they communicated. To reach the conclusion, the makerspace environment and contribution of digital fabrication tools to the PBL pedagogical approach were evaluated.

Findings

Student Collaboration

To analyze middle school students' engagement in the FabLab at their school, three key themes taken from classroom observations at the two sites were selected:

1. Defining specifications with teammates
2. Personal exploration
3. Communication about discoveries

Because each of the two schools had a different schedule and the observations were conducted in a simultaneous eight-week span, the students were at different stages. The charter school (first school site) was further along in the prototyping phase, whereas the private school (second school site) was at the research and brainstorming phase. The following sections provide examples of student interaction to illustrate these themes and snippets of their activities in the PBL process.

Defining Specifications with Teammates. Aaron[1] and his teammates, all sixth-grade students in the charter school from the first case study, were drawing their prototype in 3D in 123D Design software before using the laser cutter to cut a tangible prototype for testing. Aaron was uncertain if the scale in the rendering software, 123D Design, was proportional to real life. Thus he sought to find out by obtaining a 12-inch ruler, and he measured how large he wanted his prototype to be in reality. He went back to his laptop to check if the real-life measurement corresponded with what he had been working on in the rendering software. He discovered that the scaling in the software and in real life were different. To convince his teammates that they should change their scaling in the software, Aaron distributed 12-inch rulers to them and told them to measure in real life to discover for themselves that their scaling in the software had to change (Figure 1). This example would fall under PBL's problem investigation phase.

1. Students' names have been changed to protect the subjects' identity.

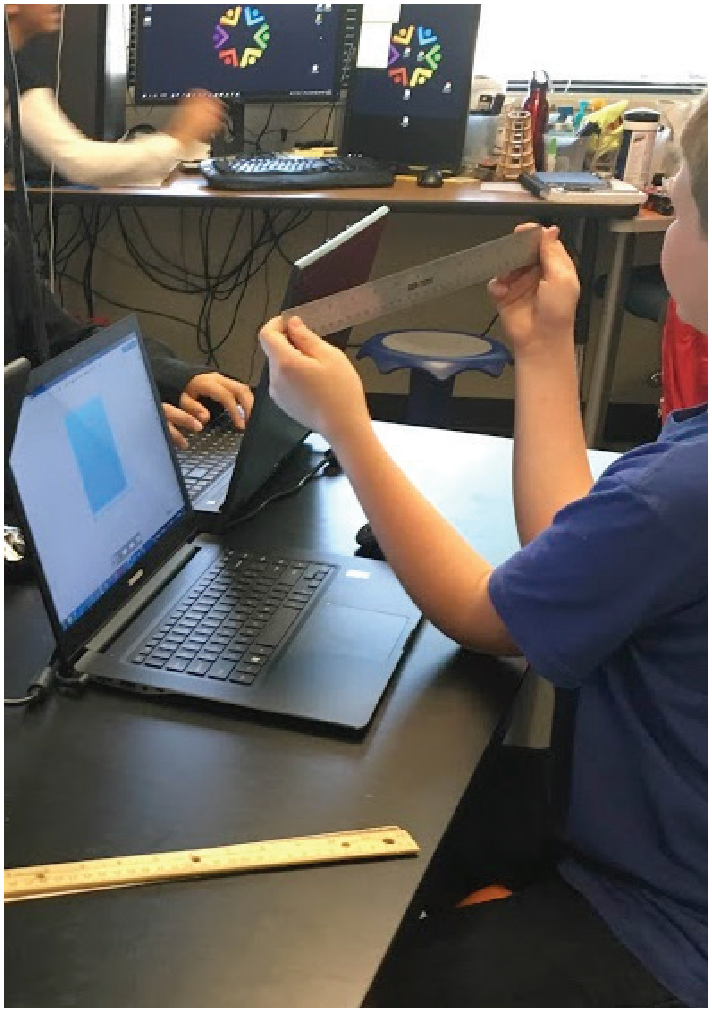
Figure 1. Aaron discusses scaling with his teammates who are opposite him at the table (not shown here).

Personal Exploration. Blake, a sixth-grade student, was designing a rather intricate product on 123D Design software. Unlike his peers, instead of extruding basic shapes such as rectangles and circles to make cuboids and cylinders, respectively, he designed distinctive 2D layers and stacked the layers on top of one another to create a more intricate 3D shape. In addition, his design had hinges. Blake used the given *x*-, *y*-, and *z*-axes in the software to toggle and rotate his virtually assembled product. He verified to see if the sides and layers fit one another by using the scaling in the software in centimeters or inches. This design was more sophisticated and advanced compared to ones produced using basic extrusion from 2D to 3D on the rendering software. An image of Blake's design is shown in Figure 2. This example would fall under PBL's problem investigation phase.

Communication about Discoveries. Colin and Dana are teammates and both are sixth-grade students. Their team

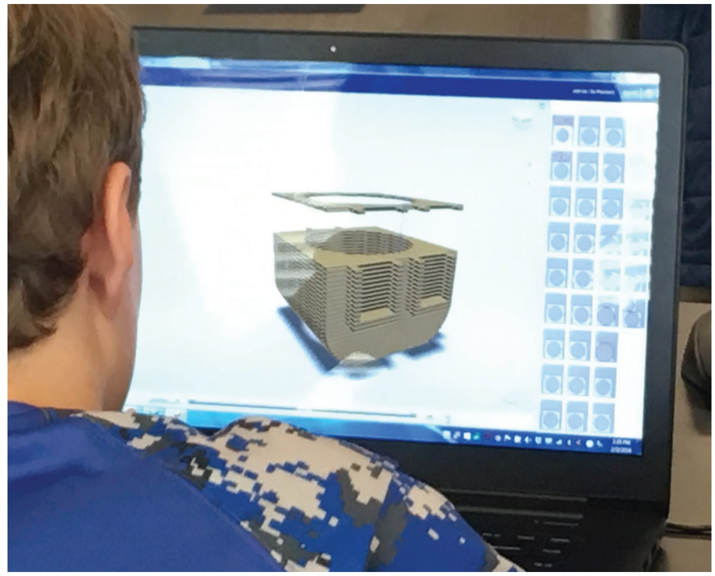
Figure 2. Blake's rendering on 123D Design software.

was quick to use the rendering software to sketch shapes and then the laser cutter to produce their cardboard prototype of a headphone hanger (refer to Figure 3). They used a trial and error method, where they held the prototype down at different lengths to the edge of the table. Then, they tested the strength of their prototype's structure by hanging real headphones on their prototype. They were aware that this variable—the distance from the table where they held the prototype down—affected how stably the headphones hung. Other variables that affected their experiment included the weight and size of the headphones, their strength when holding down the prototype, and the amount of glue they used. The students did not seem successful initially because the headphones were heavy and the cardboard was not able to bear the weight. Colin and Dana decided to use more hot glue to secure the layers of cardboard to make their prototype firmer and stronger. The students quickly discussed balance, free body forces, and some possible mathematical and physical equations that could help to improve the prototype, but they did not move on to calculate forces or look for mathematical models to explain or improve their prototype during the observing session. Images of Colin and Dana's headphone hanger prototype are shown in Figure 3. This example would fall under PBL's problem solution phase and perhaps overlaps with the process evaluation phase.

Defining Specifications. Ethan and Fiona were at the very early stages of designing their museum exhibit. They had been to museums and seen huge exhibits before, but they found out that they were unsure about how large they should make theirs. Moreover, they were uncertain about the exact numerical measurements of their exhibit board. They had

Figure 3. Colin and Dana test their headphone hanger prototype.

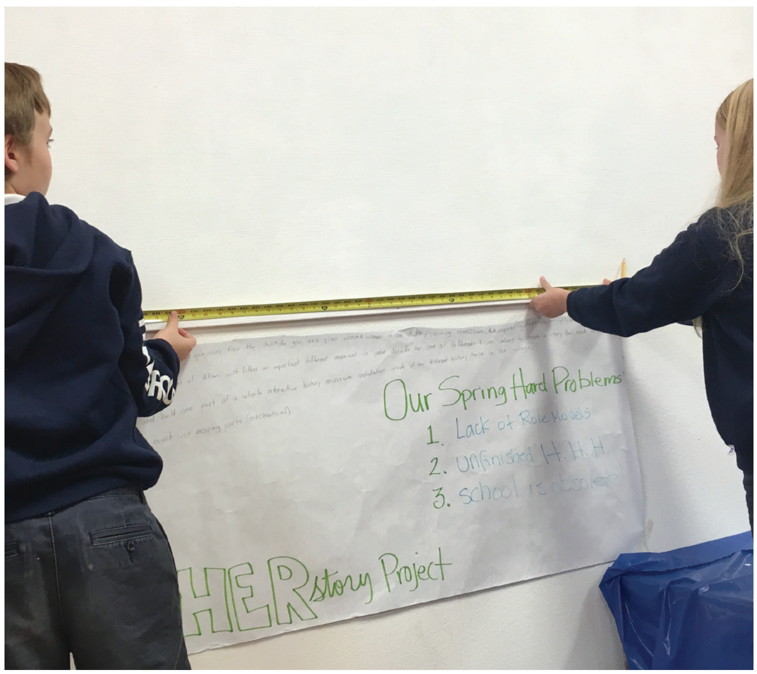

Figure 4. Ethan and Fiona discuss sizes using the measuring tape together.

some idea of how large the board should be, but needed to get numbers for the length and width of the board. Thus, both Ethan and Fiona decided to use a measuring tape, unrolled it, and placed it on a wall of the makerspace classroom to discuss how big they wanted their board to be. It turned out that both students had different conceptual ideas about size (although they used the same vocabulary term, “large,” to describe their thoughts). Using the measuring tape to discuss their project in numerical terms allowed both students to understand each other’s concepts of how large they wanted their board to be. An image of Ethan and Fiona using the measuring tape and discussing sizes of exhibit boards is shown in Figure 4. This example would fall under PBL’s problem presentation and investigation phases.

Personal Exploration. Greg is part of a team with two other students, Hannah and Ian, and they were tasked with finding out more about inspiring international women from the 20th century. This was early in the semester, and the teacher had just provided the ill-structured prompt. Greg, Hannah, and Ian decided to work independently on their own first, going online to search the Internet for information about historical women they knew of and exploring those they had not known about. There was some guidance from the teacher as to which websites they should sieve through, but the students hardly used other sources (such as library books) to look for information. It seemed that this group was quite focused on their task and could work well individually, but other groups of students who tried to work individually digressed from their original tasks. This example would fall under PBL's problem presentation phase.

Communicating about Discoveries. Continuing from their independent research, Greg, Hannah, and Ian regrouped after spending some time finding out about historical women and began to discuss what they found out and whom they found most interesting. There were women about whom all three students knew, but there were also lesser-known women that one of them had stumbled on whom they found interesting too. They spent more time discussing which one to choose, because they were unable to reach a consensus on the "best" female figure to present to their peers. After finally agreeing on a historical figure, they began discussing how their exhibit design should look. The teacher prompted the students to think about their previous experiences going to museums that feature historical figures, and to think about any interactive features they might remember from those museum exhibits. This was a good prompt that guided the students to realize that many of the history museums they had visited do not include many interactive features, and the exhibits were typically in a static poster format. They began to brainstorm and search online about feasible interactive features they could include in their exhibit design, and also how their exhibit design could best bring out certain characteristics they found interesting in the female figure they chose to present. This example would fall under PBL's problem presentation and investigation phase.

Teacher-Student Interaction

This section discusses how students and teachers interact in the FabLab while students are pursuing their team projects. Following are three examples of interaction between the students and their teacher:

Demonstrating with Tangible Objects. Janet, Katy, and Laura were in a team and they had been creating a design on the rendering software 123D Design for some time. They wanted to find out how to construct a rotating feature that could be hung on the wall. However, they were unsure about how to create a rotating feature in their design because they could not properly visualize it. Together, they approached their teacher and asked him how they could draw a 3D rotating shape in the software. To help them visualize a mechanical rotating system, the teacher opened the cover of a paper towel dispenser in the classroom and showed the students how a cylindrical structure rotated inside the dispenser. The students then asked their teacher their second question: which method is more effective, pasting the prototype on the wall or creating holes in the prototype to hook it on the wall? The teacher took them around the makerspace showing them which objects were nailed to the wall, hooked onto the wall, or hooked onto a different object such as a shelf or window instead of the wall. The teacher explained briefly that the students would have to make different measurements, calculations, and trials to test which method would work best for the prototype. These examples seemed to help the students envision what would work best for their prototype.

Discussing Prototype Failure. Matt, a fifth-grade student, was explaining to his teacher during a prototype show-and-tell lesson that his prototype had "failed." When the teacher prompted him further to explain his failure, he stated that using a small X-Acto knife to cut shapes through his material (cardboard or foam core) was difficult because his shapes turned out jagged and did not follow the specifications he had planned. He told the teacher that "if only [he] was allowed to use the laser cutter" for this assignment, he would be certain that his shapes and measurements would be more accurate.

Responding to Behavioral Issues. The science teacher at the private school had assigned only Nate to work on decorating the makerspace classroom's walls. He was drawing basic shapes such as rectangles in CorelDraw (a rendering software) to laser-cut later. Nate used the scaling in CorelDraw to measure his 2D and 3D shapes, then scaled them according to the real-life sizes that he would laser-cut later. He seemed very engaged in this particular task the teacher had given him, and he was working quietly on his own laptop. This was not the same task the teacher had given other students—only Nate was working on this. Other students were in their teams discussing the deliverables due soon, starting shared Google folders in their Google Drive, and brainstorming team names. It was discovered later that the teacher had set Nate an individual task involving rendering software and higher-tech tools in the makerspace because she knew that Nate had antagonistic behavioral issues that made working with teammates very difficult, but she still wanted Nate to have a positive experience in the FabLab, so that she could ease him into a group later on and hope that he would not be repelled by group work in a FabLab.

Discussion

From the observations at the two middle school FabLabs, we see that a variety of influences of digital fabrication exist with regard to PBL in a FabLab environment.

After evaluating both schools' FabLabs against the three important characteristics of PBL that Savery (2015, p. 15) provided, these are the findings listed: the teachers strove as much as possible to be facilitators instead of instructors, tried to the best of their capability to guide students to direct their own learning journey, and developed ill-structured problems for the class sessions.

With this, there is a certain notion that there would be maximum collaboration between students (peers) and perhaps between students and teachers, since a key maker mindset characteristic is collaborative. Most of the examples observed follow the process of "designing, personalizing, sharing, reflecting" (Brennan, 2015), and there are signs of computational participation with community-based perspectives embedded in how the teachers structure the FabLab classes and project topics (Kafai & Burke, 2014). Although most examples show student collaboration because students were strongly encouraged to work in teams, the final example of Nate, who preferred to work alone with FabLab tools (but still within the PBL approach), brings some thoughts about the potential of PBL in a FabLab setting. Perhaps the maker mindset that includes playfulness and collaboration does not always have to be accentuated in a PBL-driven FabLab space. The teacher's interaction with Nate was different from that of other students, but she was still able to guide him through a decently ill-structured problem in a PBL manner.

From the other examples of student-student and teacher-student interaction in the FabLab's PBL setting, we see that the students do show a strong sense of agency in their projects and are able to construct questions that are meaningful to their project to ask their teacher (their facilitator, in this case). The students' communication among one another about their discoveries and/or insights is an important way of sharing authentic ideas, which is key to the idea of constructionist learning, as has been described by scholars such as Papert and Vygotsky. The FabLab's digital fabrication tools may have spurred some of the students' discoveries and/or insights, and correlated with their communication of authentic ideas in a FabLab setting, but there is currently insufficient causal evidence to conclude that the tools caused improvement in how the students communicated. There is definitely opportunity for deeper research here.

Limitations

Due to the research focus on PBL in FabLab environments that concentrate more on STEM, this study has left out topics of research and discussion of where digital fabrication could lead, for example arts education, community building, teamwork and engagement, and more. This study has also been limited to two high-income middle schools in California in the United States, and the styles of how these FabLab classes were conducted could differ between higher-income and lower-income communities.

The timeline for the research project was also rather short, 9 months in total from research question generation to conclusion of the study, including 3 months dedicated to visiting research sites, conducting FabLab observations on average once a week, and interviewing teachers. If this research timeline were lengthened by more than a year, and if there were a larger number and wider variety of research sites, the examples of interactions might be more concrete. It would also be preferable to include video recordings in the qualitative research process, in order to describe the students' interactions with their peers and tools more accurately, and quote them appropriately.

Future Research

A feasible next step from this study is to look at PBL in FabLabs through a more quantitative lens. This study had been very much based on qualitative observations and interviews. For example, future research could look into using learning analytics methods to discover how PBL can be measured more quantitatively in FabLab environments. Additionally, future research could investigate the differences in the STEM scores of students who are engaged in problem-based FabLab activities compared to students who do not engage in problem-based FabLab activities at various levels of schooling (not only at middle school).

Other evaluation studies could also be conducted. For example, in the short term, a study could investigate middle school students' attitudes and understanding of the term "engineering" after participating in a series of FabLab classes or workshops on digital fabrication. Another possible and important avenue for future research is education equity in the FabLab context. Does the presence of a FabLab in a school increase education equity or widen the equity gap between high-income and low-income communities? How would higher-income students' behavior differ from lower-income students' behavior in the FabLab? Would students, regardless of socioeconomic status, gain the same level of understanding if digital fabrication was connected to STEM topics taught in traditional classrooms?

Beyond the scope of digital fabrication in schools and connecting digital fabrication and STEM more explicitly in FabLabs in schools, future research could explore "maker" identities that students, teachers, and the school administrators cultivate or develop through engaging in FabLab activities. This would be interesting to examine and would produce deeper academic comprehension about how people construct their identities toward making and via making.

Conclusion

This study on PBL in FabLabs may be a short study compared to other larger scale, longer term research projects. Nevertheless, this study offers an insight into student and teacher dynamics related to a PBL approach in a nontraditional, technology-rich learning environment.

The maker movement is on the rise now in many different parts of the world, and education technology is a field that is growing rapidly. Digital fabrication is expanding into schools quickly, but this huge potential has to be mediated with appropriate curriculum, appropriate pedagogy, and vigilant teaching.

From this study, examples of student interaction with regard to a PBL approach have been observed and illustrated. Future work could be pinpointed more directly to study specific PBL phases separately in nontraditional learning environments such as FabLabs. A comparative study between PBL and other forms of inductive pedagogical approaches for engineering education in FabLabs would also be interesting. Teacher-student dynamics are also a vital component of PBL, and more research can be conducted to study how teacher-student interaction could facilitate and contribute to learning in a maker-oriented, technology-rich environment.

References

Awang, H., & Ramly, I. (2008). Through problem-based learning: Pedagogy and practice in the engineering classroom. *International Journal of Human and Social Sciences*, *2*(4), 18–23.

Barrows, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. *New Directions for Teaching and Learning*, *1996*(68), 3–12.

Barrows, H. S. (2000). *Problem-based learning applied to medical education*. Southern Illinois University School of Medicine.

Barrows, H. S., & Tamblyn, R. M. (1980). *Problem-based learning: An approach to medical education*. Springer.

Berland, Matthew. (2016). Making, tinkering, and computational literacy. *Makeology: Makers as Learners*, *2*, 196.

Blikstein, P. (2013). Digital fabrication and 'making' in education: The democratization of invention. *FabLab of Machines, Makers and Inventors*, 203–222. Retrieved December 10, 2015.

Brennan, K. (2015). Beyond technocentrism. *Constructivist Foundations*, *10*(3).

Bull, G., Gerald, K., & Gibson, D. (2009). Editorial: A rationale for incorporating engineering education into the teacher education curriculum. *Contemporary Issues in Technology and Teacher Education, 9*(3), 222–225.

Cole, M., & Wertsch, J. V. (1996). Beyond the individual-social antinomy in discussions of Piaget and Vygotsky. *Human development*, *39*(5), 250–256.

Davee, S., Regalla, L., & Chang, S. (2015, May 1). Makerspaces highlights of select literature. Retrieved December 9, 2015, from http://makered.org/wpcontent/uploads/2015/08/Makerspace-Lit-Review-5B.pdf

Dewey, J. (1902). *The child and the curriculum*. Chicago, IL: University of Chicago Press.

Dewey, J. (1938). *Experience and Education* (p. 18). New York: Touchstone.

DiSessa, A. A., & Cobb, P. (2004). Ontological innovation and the role of theory in design experiments. *Journal of the Learning Sciences*, *13*(1), 77–103.

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American Psychologist*, *34*(10), 906.

Freire, P. (1972). *Pedagogy of the oppressed*. New York: Herder and Herder.

Freudenthal, H. (1973). *Mathematics as an educational task*. Springer Science & Business Media.

Froebel, F., & Hailmann, W. N. (1901). *The education of man*. New York: D. Appleton.

Gershenfeld, N. (2012, September 27). How to make almost anything. Retrieved September 14, 2015.

Hmelo-Silver, C. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, *16*(3), 235–266.

Hodson, D., & Hodson, J. (1998). From constructivism to social constructivism: A Vygotskian perspective on teaching and learning science. *School Science Review, 79*(289), 33–41.

Jaramillo, J. A. (1996). Vygotsky's sociocultural theory and contributions to the development of constructivist curricula. *Education, 117*(1), 133.

Kafai, Y. B., & Burke, Q. (2014). *Connected code: Why children need to learn programming*. MIT Press.

Kilpatrick, W. H. (1918). *The project method: The use of the purposeful act in the educative process* (No. 3). Teachers College, Columbia University.

Kilpatrick, W. H. (1921). *Dangers and difficulties of the project method and how to overcome them: A symposium*. Columbia University Press.

Kuznetsov, S., & Paulos, E. (2010, October). Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (pp. 295–304). ACM.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Major, C. H., & Palmer, B. (2001). Assessing the effectiveness of problem-based learning in higher education: Lessons from the literature. *Academic Exchange Quarterly*, *5*(1), 4–9.

Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research (J-PEER), 5*(1), 4.

Montessori, M. (1965). *Spontaneous activity in education*. New York: Schocken Books.

Mota, C. (2011, November). The rise of personal fabrication. In *Proceedings of the 8th ACM Conference on Creativity and Cognition* (pp. 279–288). ACM.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism*, *36*(2), 1–11.

Piaget, J. (1980). *The constructivist approach: Recent studies in genetic epistemology*. Geneva: Foundation Archives Jean Piaget.

Posch, I., & Fitzpatrick, G. (2012, November). First steps in the FabLab: Experiences engaging children. In *Proceedings of the 24th Australian Computer-Human Interaction Conference* (pp. 497–500). ACM.

Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education*, *95*(2): 123–138.

Prince, M. J., & Vigeant, M. (2006). Using inquiry-based activities to promote understanding of critical engineering concepts. American Society for Engineering Education Annual Conference, Chicago, IL.

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S. Barrows*, *9*, 5–15.

Steinemann, A. (2003). Implementing sustainable development through problem-based learning: Pedagogy and practice. *Journal of Professional Issues in Engineering Education and Practice*, *129*(4), 216–224.

Torp, L. (2002). *Problems as possibilities: Problem-based learning for K–16 education*. ASCD.

Turkle, S., & Papert, S. (1990). Epistemological pluralism: Styles and voices within the computer culture. *Signs: Journal of Women in Culture and Society*, *16*(1), 128–157.

Von Glasersfeld, E. (1984). An introduction to radical constructivism. In P. Watzlawick (Ed.), *The invented reality* (pp. 17–40). New York: Norton.

Wadsworth, B. J. (1996). *Piaget's theory of cognitive and affective development: Foundations of constructivism*. Longman.

Appendix 1

Observation Checklist

1. What resources are there in the FabLab that have any relation to math?
2. Which resources are students using in this class? Are there signs that the mathematical aspects are being used, realized, thought about, or discussed?
3. Are students mostly doing individual work or teamwork projects?
4. What tools that relate to mathematics are students using?
5. How effectively are the students using these tools? Would more explicit attention to math concepts (e.g., computation, measurement) help? Are they checking with their teacher(s) about how to use these tools and do math concepts come up?
6. Are there any math concepts presented in class that could be applied to the students' projects?
7. Do the conversations students are having with their peers and teachers touch on math concepts?
8. How does the presence of math in a school's FabLab differ in various schools?

Appendix 2

Interview Protocol for Teachers

1. How do you see the role of mathematics in creating and design in FabLab classes? What forms or areas of mathematics?
2. Do the state's middle school Mathematics and Engineering/Design requirements play a part in your FabLab classes? Are FabLab classes considered supplementary electives?
3. Can you please describe if and how you build in lessons in your FabLab class to engage students in areas of STEM? Are the classes mostly student-directed independent learning?
4. Can you describe any indications that the FabLab classes affect the learning in any other classes?
5. How much student development (in terms of knowledge about the STEM process and work attitude) have you noticed by having FabLab classes?
6. What challenges do you face in your FabLab class? Any suggestions or recommendations?

Monica Chan is a doctoral student at Teachers College, Columbia University in the Instructional Technology & Media program. She is a member of the Snow Day Learning Lab that Professor Nathan Holbert leads, and a recipient of the Arthur Zankel Urban Fellowship at Teachers College. Her research interests include makerspaces, emerging learning technologies, and K–12 STEM and computer science education. Previously, she graduated from Stanford University with a BS in Mechanical Engineering and an MA in Learning, Design & Technology (Education). She completed her honors thesis with Professor Paulo Blikstein at Stanford's Transformative Learning Technologies Lab.

Paulo Blikstein is an assistant professor at the Stanford University Graduate School of Education where he directs the Transformative Learning Technologies Lab and the global FabLearn Program. Blikstein's research focuses on how new technologies can deeply transform the learning of science, technology, engineering, and mathematics. He creates and researches cutting-edge educational technologies, such as computer modeling, robotics, digital fabrication, and rapid prototyping, creating hands-on learning environments in which children learn STEM disciplines by building sophisticated projects and devices. He also focuses on the application of data mining and machine learning for the assessment of hands-on, project-based learning. Blikstein was a pioneer in bringing the maker movement to schools, and started the first educational program around digital fabrication in schools, FabLearn Labs (formerly FabLab@School). His group has built advanced digital fabrication labs and has conducted research in middle and high schools in the United States, Russia, Mexico, Spain, Australia, Finland, Brazil, Denmark, and Thailand.