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# On Problem-Based Learning in Science, Technology, Engineering and Mathematics

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**Abstract** – In this paper, we present an overview of Problem-based Learning and discuss the possibility of adopting this method for Science, Technology, Engineering and Mathematics. The authors have been recently awarded a National Science Foundation grant to implement and examine this approach.

## 1 Introduction

Developied in medical field in 1969, Problem-based learning (PBL) has been presented as an alternative, innovative, and yet essential approach to learning. PBL has prevailed ever since and spread beyond the medical disciplines. PBL introduces a change in the delivery of instruction. In an attempt to enhance and optimize the educational outcomes, PBL focuses on an active, integrated, self-directed, collaborative student-centered environment [1]. In this environment, the delivery of instruction is moved from the traditional teacher-centered approach to the involvement of peer teaching and learning in small groups where learning happens through the social construction of knowledge using a real-world problem. Barrows [2] lists the original key components:

1. Learning is student centered.
2. Learning occurs in small student groups.
3. Teachers are facilitators or guides.
4. Problems form the original focus and stimulus for learning.
5. Problems are a vehicle for development of problem solving skills.
6. New information is acquired through self-directed learning.

A clear understanding of PBL basic tenets, practices and philosophy are the basis of implementation. Therefore, training the PBL facilitators is of utmost importance because of their critical role in the PBL process. At the same time PBL is demanding a significant change in the

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mindsets of both students and teachers for a successful implementation. In PBL, students must outline an approach for addressing the presented problem based on their current knowledge of the subject. After establishing a plan, students receive problem-solving guidance from instructors. Armed with this additional insight, students improve their plan and proceed to implement it. After implementation, students evaluate their problem-solving method, otherwise known as a closed-loop process. Finally, students share their accomplishments with others inside and outside of the classroom [3].

Jonassen [4] provides additional clarification on best PBL practices, to include the previously discussed breakdown of problem typology, from well-structured problems to more complex ill-structured problems. Jonassen details a structured system of problem-scaffolding and case components (examples) to ensure student development of problem-solving skills. Finally, a closed-loop process has been shown to best promote student learning [5]. That is when learners evaluate the reasoning process, the quality of information sources, and their content knowledge. Through the process, students learn to critically evaluate and improve their problem-solving abilities.

## 2 Rationale

The Next Generation Science Standards (NGSS) was introduced in 2013 as a reform standard that demanded realignment of “curriculum, instruction, and assessment to match inquiry and problem-solving approaches” [6]. NGSS aims to prepare students for real-world demands and academic achievement in arts and science, mathematics, and English language. NGSS was developed, in part, due to U.S. students’ low scores in problem solving and critical thinking on international assessments.

Education systems overwhelmingly employ traditional teaching methods used for generations despite vast technological and societal changes. According to the High School Survey of Student Engagement (HSSSE), two-thirds of students are bored in class every day [7]. Students most commonly attributed boredom to uninteresting and irrelevant material as well as minimally interactive teaching. In contrast, students reported interest and engagement for activities that included discussion, debate, group projects, and technology experiences. Even more, digital information is exponentially expanding. According to a 2011 IBM report, 90% of the world’s data was created in the two years prior to the report. The average U.S. high school student crams nearly 11 hours of digital content into 7.5 hours daily by multitasking on mobile devices [8], consequently negotiating billions of data streams. Today’s students require an interactive environment with relevant authentic problems to connect learning to life and match their digital world. Industry-aligned problem-based learning (PBL) addresses the issue to engage students, provide relevant contextual learning, and expand the critical thinking skills vital to navigating the quickly changing technological world.

In light of the increasing demands for a Science, Technology, Engineering, and Mathematics (STEM)-educated workforce, educators and students alike call for a change in the current education system. NGSS calls for teaching of science to be focused on a limited number of core ideas for students to learn in greater depth. The assistant superintendent of the Hawaii Office of Curriculum, Instruction, and Student Support states [9], "Unlike previous content standards the NGSS is aimed to excite young people about science and engineering; [and] effectively connects scientific concepts to careers”. The President’s Council of Advisors on Science and Technology recommends increased authentic discovery-based courses along with partnerships between stakeholders and private-public organizations [10]. Research suggests that problem-based inquiry fits this description as it engages students in question generation, communication, collaboration, creativity, critical thinking, and teamwork ([11] and [12]). PBL provides an environment to prepare the high school students for higher education and beyond. Students learn and retain information better and longer when they are actively engaged in their own learning in an environment that is designed to motivate them. When students work in teams, they play a key role in constructing their own learning through active participation and creation of their own outcomes. Studies of inquiry-based science in [13] and [14] found that an inquiry approach was equally effective among low-income diverse ethnic and linguistic subgroups. Additionally, PBL students also have been more able to apply their learning to new problems in a variety of settings [15].

Educators are challenged, especially those serving low-income diverse students from underserved schools, to meet the learning demands of NGSS. PBL provides students with a learning environment where students are stimulated to think creatively and use problem-solving skills. In an inquiry classroom students actively participate in their own learning (individually or in small groups) on real problems and towards their own understanding and achievement of concrete outcomes ([12], [16], [17], [18], [19], and [20]). PBL is an interactive process for engaging teachers and students in solving relevant real-world problems that emerge from students' questions in relation to NGSS standards. Our recently funded project is guided by social constructionism theory of learning [21] and Situated Learning Theory [22] that undergird PBL. Both of these lenses will guide our data analysis and discussion in our project.

## 3 Theoretical Background

Social constructionism was influenced by the work of the Russian psychologist Lev Vygotsky ([23] and [24]). Vygotsky argued learning leads to development and that this learning takes place in a social context with others. Social constructionism is an ongoing and dynamic learning process that not only supports, but also aligns with a PBL environment [25].

Constructionism posits that knowledge is built and not supplied. Individuals are constantly constructing the reality of their world and their knowledge through social interaction ([26] and [27]) This means when individuals are engaged in building something shared and external together, knowledge is constructed. In [28], Kafia and Resnick view constructionism as being involved in two intertwined types of construction: the construction of external artifacts and the construction of knowledge. They also stress several dimensions that distinguish constructionism from other learning theories. First, when others define knowledge acquisition in cognitive terms, constructionism considers the importance of affect and argues that learners engage more on projects that are personally meaningful. Second, constructionism emphasizes diversity of both learning styles and representation of knowledge. Third, constructionism suggests a strong relation between design and learning. This is why Kafia and Resnick believe that activities that involve designing or constructing (as called for in the new standards) provide a rich basis for learning. Lastly, constructionism values the social nature of learning and the vital role of the community. "There is a growing appreciation for the role that communities play in the learning process: community members act as collaborators, coaches, audiences, and co-constructors of knowledge" ([28], p.6).

According to Vygotsky [23] scaffolding is an instructional support that teachers can give to students when they are learning new skills, content, or knowledge. When teachers are providing their students with a set of sequential step-by-step skills that are broken down into smaller chunks, the target objective will be reached faster. Learners' readiness for new knowledge is also facilitated through what Vygotsky labeled the zone of proximal development. This is a bridge between what learners can do on their own and what they are able to accomplish with another person's help (such as a teacher, friend, other classmate, or parents). The emergence of social constructionism, based on Vygotsky's work, emphasized the fact that learning happens during social interaction; in other words, it is shaped through participation and social negotiation.

In the early 1990s Lave and Wenger [22] viewed learning as a social phenomenon that comes from individual experience of participating in daily life. In other words, learning is a process of social participation and engaging in a "community of practice," that requires social interaction and collaboration. This instructional approach is referred to as the Situated Learning Theory. According to the situated learning theory, when students are actively participating in the learning experience, they are more apt to learn. Examples of the environments that contribute meaningfully to students learning are field trips, music, education, sport camps, and hands-on laboratories. By placing students in these situations, students become a part of the learning activity. Their success depends on students' "social interaction and kinesthetic activity".

Here learning is unintentional and situated within authentic activity, context, and culture "deliberately designed to de-skill" [29]. In this environment learners/students are going through the process of "enculturation" and learning simply by participating in the community of practice. Therefore, the learning process includes social interaction, collaboration and knowledge construction.

Herrington and Oliver [30] identify eight critical characteristics for situated learning that has provide a valuable framework in analyzing the learning process. These characteristics are: (1) authentic contexts, (2) authentic activities, (3) access to expert performances and modeling, (4) multiple roles and perspectives, (5) collaborative construction of knowledge, (6) reflection, (7) articulation, and (8) coaching and scaffolding. Both constructionism and situated learning theory provide us with lenses through which to analyze the construction of knowledge and the learning of math and science materials for both students and their teachers. Through these lenses we explore the diversity of students' learning style, reproduction of knowledge in deeper format, and investigate the social nature of learning. The constructionism lens further helps us to explore the construction of external artifacts through the meanings and significance they had for students.

## 4 PBL in STEM Effectiveness and Potential

Meta-analyses findings indicate PBL is as effective as traditional learning for content knowledge and exceeds traditional learning methods for teaching critical thinking, communication, collaboration, and applying knowledge to real world situations ([5], [31] and [32]). PBL is used with students of any age and skill level [3]. With a developmental focus on personal growth, making meaning of the larger world, and discovery, adolescents are at an ideal stage to respond to a self-directed problem-solving curriculum [33]. Results of several high school and college PBL studies indicate PBL as effective as or more effective than traditional instructional approaches ([34] and [35]), especially with low-income students [36]. STEM-focused PBL summer programs have been shown to also increase STEM career aspirations ([37] and [38]). The University of Akron Upward Bound Math-Science (UBMS) program, a 6-week residential program with classes in math, science, and composition changed from a lecture-based to inquiry-based approach. Over a 5-year period, results showed significant increases in GPA, decreased anxiety towards math and sciences, and increased STEM self-efficacy. The majority of participants entered a STEM degree program following high school graduation [38]. Despite promising results, very few schools offer PBL curriculum [39]. Furthermore, much of the research on PBL at the high school and college levels lacks structure and identification of what works for whom ([39] and [40]) as well as appropriate teacher training and support [41].

As the speed of information creation increases, students need stronger critical thinking and self-directed learning skills to navigate valid information sources. PBL emphasizes problem-solving and critical thinking in addition to content knowledge [40]. An important component to student engagement is the use of authentic problems to provide real-life context and direct application of learning. A key to the success of PBL is providing an ill-structured problem that scientists and engineers might face in the real world [3]. The definition of authentic environment varies, from simulations to outcomes with real-world impacts. Larmer argues the most powerful, engaging, and effective problems for students are the problems with the most real-world impacts [42]. King, Newmann, & Carmichael also agree that PBL must have real-world contact and impacts outside the classroom [43].

Alignment with industry further provides opportunity for contextualizing knowledge [39]. There specifically exists a Pacific Institute for the Mathematical Sciences (PIMS) model that provides PBL with real-world industry problems, an effective instructional design model [44]. Limited research exists on instructional design methods, though two small studies at the postsecondary level show enhanced engagement and learning through this approach ([45] and [46]). At the high school and college levels, STEM industry involvement has been shown to enhance student's engagement in content, connections to real-life application, and interest in STEM careers for low-income first-generation students. Many rural and geographically-isolated students face limited exposure to STEM careers. Involvement with STEM industries, such as mentoring and job shadowing can increase awareness and realistic expectations of local STEM opportunities [47]. Rural students previously unable to relate science content to life, were able to relay contextual connections and described increased STEM interest after only one STEM career-related field trip [48]. Geographically-isolated students in Kentucky and Tennessee viewed STEM fields more positively after participation in an engineering project based on a locally-relevant problem [49]. Finally, low-income first-generation students at The University of Akron improved study and collaboration skills as well as showed higher high school graduation rates after participating in a 4-week program with inquiry-based STEM instruction and local STEM industry mentoring [50]. Therefore, our project, which takes place in Hawaii, provides the perfect environment to research the effectiveness of a well-structured industry-aligned PBL curriculum for low-income first-generation and geographically isolated students.

## 5 Conclusion

Our project will deliver effectiveness data on a novel approach to engage today's technologically savvy student whose informal learning environment drastically differs from the traditional K-16 model. As previously outlined, the U.S. education system is not producing the STEM workforce to meet tomorrow's needs. Millions of geographically-isolated and low-income potential first-generation studentsthe students least likely to pursue STEM degreesawait engagement, exposure, and real-world learning to demonstrate the relevance of STEM education. According to the results of several meta-analyses at the postsecondary level, PBL appeared to be as effective as traditional learning for content knowledge and more effective at long-term learning and application. While PBL research at the secondary and college levels is limited and commonly lacks a structured PBL environment, evidence is promising for the effectiveness of PBL with both high school/college and low-income students. Furthermore, research and best practices point to real life application and involvement of STEM industries to promote interest and engagement in STEM education, especially for low-income and geographically-isolated students. Our project takes structured PBL one step further by aligning local STEM industries for contextual learning and STEM pipeline development. Beyond immediate project results, longitudinal data will be collected and available for future projects to study the impact on the ultimate goalSTEM degree completion.

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## References

[1] R. Matheson and B. Haas, "Exploring the foundations for problem-based learning," in Problem-based Learning in Health and Social Care. Chichester: Wiley-Blackwell; 2010. pp. 9-24

[2] H. S. Barrows, "Problem-based learning in medicine and beyond: A brief overview," in Bringing problem-based learning to higher education: Theory and practice. San Francisco, CA: Jossey-Bass Inc.; 1996. pp. 3-12.

[3] A. Lockhart and J. Le Doux, "A partnership for problem-based learning," in The Science Teacher; 2005; 72(9): pp. 29-33.

[4] D. Jonassen, "Supporting problem solving in PBL," in Interdisciplinary Journal of Problem-based Learning; 2011;5(2): pp. 95-119.

[5] A. Walker and H. Leary, "A problem-based learning meta-analysis: Differences across problem types, implementation types, disciplines, and assessment levels," in Interdisciplinary Journal of Problem-based Learning; 2009;3(1): pp. 11-43.

[6] N. Nariman and J. Chrispeels, "PBL in the era of reform standards: challenges and benefits perceived by teachers in one elementary school," in Interdisciplinary Journal of Problem-based Learning; 2016; 10(1).

[7] E. Yazzie-Mintz, "Charting the path from engagement to achievement: A report on the 2009 High School Survey Student Engagement." Bloomington, IN Center for Evaluation and Education Policy; 2010.

[8] V. J. Rideout, U. G. Foehr, and D. F. Roberts, "Generation M2: Media in the Lives of 8-18-Year-Olds: A Kaiser Family Foundation Study." Menlo Park, CA; 2010.

[9] Hawai'i State Department of Education. Hawai'i State BOE approves science for the next generation [Internet]. 2016, Feb 19 [cited 2016 Jul 21]. Available from http://www.Hawai'ipublicschools.org/ConnectWithUs/MediaRoom/PressReleases/Pages/NGSS.aspx

[10] President's Council of Advisors on Science and Technology (US). Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics [Internet]. Washington, DC: Executive Office of the President (US); 2012 [cited 2016 Jun 20]. Available from http://www.whitehouse.gov/sites/default/files/microsites/ostp/fact_sheet_final.pdf.

[11] P. A. Ertmer and K. D. Simons, "Jumping the PBL implementation hurdle: supporting the efforts of K-12 teachers," in Interdisciplinary Journal of Problem-based Learning; 2006; 1(1): pp. 40-54.

[12] C. E. Hmelo-Silver, "Problem-based learning: what and how do students learn?" in Educational Psychology Review; 2004; 16(3): pp. 235-266.

[13] S. Lynch, J. Kuipers, C. Pyke, and M. Szesze, "Examining the effects of a highly rated science curriculum unit on diverse students: Results from a planning

grant" in Journal of Research in Science Teaching; 2005; 42: pp. 921-946.

[14] P. Cuevas, O. Lee, J. Hart, and R. Deaktor, "Improving science inquiry with elementary students of diverse backgrounds" in Journal of Research in Science Teaching; 2005; 42: pp. 337-357.

[15] J. Boaler, "Open and closed mathematics: Students' experiences and understanding" in Journal of Research in Mathematics Education; 1998; 29(1):41-62.

[16] H. S. Barrows, An How to design a problem-based curriculum for the preclinical years. New York: Springer Publication, 1985.

[17] P. C. Blumenfeld, E. Soloway, R. W. Marx, J. S. Krajik, M. Guzdial, and A. Palinscar, "Motivating project-based learning: Sustaining the doing, supporting the learning," in Educational Psychologist; 1991; 26(3 & 4):pp. 369-398.

[18] M. N. Gltek, "Effect of project based learning on learning outcomes in the 5th grade social studies course in primary education," in Educational Sciences: Theory and Practice; 2005;5(2):pp. 548-556.

[19] R. W. Marx, P. C. Blumenfeld, J. S. Krajik, and E. Soloway, "Enacting project-based science," The Elementary School Journal; 1997; 97(4):pp. 341-358.

[20] D. G. Moursund, Project-based learning using information technology. Eugene, OR: ISTE Publication, 1999.

[21] S. Papert, "Situating constructionism," in Constructionism: Research reports and essay; 1991; pp. 1-11.

[22] J. Lave and E. Wenger, Situated Learning: Legitimate Peripheral Participation. Cambridge, UK: Cambridge University Press, 1990.

[23] L. S. Vygotsky, Mind and Society. Cambridge, MA: Harvard University Press, 1978.

[24] L. S. Vygotsky, Thought and language. Cambridge, MA: MIT Press, 1986.

[25] S. A. Barab, K. E. Hay, K. Squire, M. Barnett, R. Schmidt, K. Karrigan, L. Yamagata-Lynch, and C. Johnson, "Virtual solar system project: Learning through a technology-rich, inquiry-based, participatory learning environment," in Journal of Science Education and Technology; 2000; 9(1): pp. 7-25.

[26] E. Spodak, "Technoconstructivism for the undergraduate foreign language classrooms," in Foreign Language Annals.; 2005; 38(3): pp. 428-435.

[27] M. J. Wheatley, Finding our way: Leadership for an uncertain time. San Francisco: Berrett-Koehler Publishers, 2007.

[28] Y. Kafai, M. Resnick, (Eds.) Constructionism in practice: Designing, thinking, and learning in a digital world. Mahwah, NJ: Lawrence Erlbaum Associates, Inc. Publishers, 1996.

[29] J. S. Brown and P. Duguid, "Stolen Knowledge," in Situated Learning Perspectives; 1996; pp. 47-56.

[30] J. Herrington and R. Oliver, "Critical characteristics of situated learning: Implications for the instructional design of multimedia," Edith Cowan University (AU):2000. Available from http://methodenpool.uni-koeln.de/situierteslernen/herrington.pdf.

[31] L. Darling-Hammond, B. Barron, P. D. Pearson, A. H. Schoenfeld, E. K. Stage, T. D. Zimmerman, TD, G. N. Cervetti, and J. L. Tilson, Powerful learning: what we know about teaching for understanding. San Francisco, CA: John Wiley & Sons, Inc.; 2009.

[32] J. Strobel and A. van Barneveld, "When is PBL more effective? Meta-synthesis of meta-analysis comparing PFL to conventional classrooms," in Interdisciplinary Journal of Problem-based Learning; 2009; 3(1). doi: 10.7771/1541-5015.1046.

[33] R. Halpern,P. Heckman, and R. Larson, "Realizing the potential of learning in middle adolescence," 2013; Retrieved from http://www.howyouthlearn.org/pdf/Realizing %20the%20Poential%20of %20Learning %20in %20Middle %20Adolescence.pdf.

[34] J. R. Mergendoller, N. L. Maxwell, and Y. Bellisimo, "The effectiveness of problem-based instruction: A comparative study of instructional methods and student characteristics," Interdisciplinary Journal of Problem-based Learning; 2006; 1(2). doi: 10.7771/1541-5015.1026.

[35] J. R. Savery, "Overview of problem-based learning: definitions and distinctions," in Interdisciplinary Journal of Problem-based Learning; 2006; 1(1): pp 9-20. doi: 10.7771/1541-5015.1002.

[36] S. A. Gallagher and J. J. Gallagher, "Using problem-based learning to explore unseen academic potential," in Interdisciplinary Journal of Problem-based Learning; 2013; 7(1).

[37] J. Zhe, D. Doverspike, J. Zhao, P. L. Lam, and C. Menzemer, "High school bridge program: A multidisciplinary STEM research program," in Journal of STEM Education; 2010; 11(1): pp. 61-68.

[38] P. C. Lam, R. Srivatsan, D. Doverspike, J. Vesalo, and P. R. Mawasha, "A ten-year assessment of the pre-engineering program for under-represented, low income and/or first generation college students at the University of Akron," in Journal of STEM Education; 2005; 6(3): pp. 14-20.

[39] R. D. Atkinson and M. J. Mayo, "Refueling the U.S. Innovation economy: Fresh approaches to science, technology, engineering, and mathematics (STEM) education," Washington, D.C.: The Information Technology & Innovation Foundation; 2010. Retrieved on February 1, 2014 from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1722822.

[40] J. Ravitz, "Introduction: Summarizing findings and looking ahead to a new generation of PBL research," in Interdisciplinary Journal of Problem-based Learning; 2009; 3(1). doi: 10.7771/1541-5015.1088.

[41] A. Asghar, R. Ellington, E. Rice, F. Johnson, and G. M. Prime, "Supporting STEM education in secondary science contexts," in Interdisciplinary Journal of Problem-based Learning; 2012; 6 (2). doi: 10.7771/1541-5015.1349.

[42] J. Larmer, "PBL: What does it take for a project to be "authentic"? Edutopia," 2013, June 5. Retrieved February 1, 2014 from http://www.edutopia.org/blog/authentic-project-based-learning-john-larmer.

[43] M. B. King, F. M. Newman, and D. L. Carmichael, "Authentic intellectual work: Common standards for teaching social studies," in Social Education; 2009; 73: pp. 43-49.

[44] Pacific Institute for the Mathematical Sciences. Industrial Workshops [Internet]. 2016 [cited 2016 Jun 30]. Available from https://www.pims.math.ca/industrial/industrial-workshops.

[45] N. Dabbag and C. Blijd, "Students' perceptions of their learning experiences in an authentic instructional design context," in Interdisciplinary Journal of Problem-based Learning; 2010; 4 (1). doi: 10.7771/1541-5015.1092.

[46] J. Marshall and W. Marshall, "A laboratory-based, problem-solving pedagogy prepares students to hit the job market running!" 2012 American Society for Engineering Education Annual Conference; 2012, June; San Antonio, TX.

Paper retrieved from http://www.asee.org/ public/conferences/8/papers/3527/view.

[47] B. C. Hutchins and P. Akos, “Rural high school youth’s access to and use of school-to-work programs,” in The Career Development Quarterly; 2013; 61: pp. 210-225. doi: 10.1002/j.2161-0045.2013.00050.

[48] T. Hutson, S. Cooper, and T. Talbert, “Describing connections between science content and future careers: Implementing Texas curriculum for rural at-risk high school students using purposefully-designed field trips,” in Rural Education; 2011; 33: pp. 37-47.

[49] M. Boynton and F. Hossain, “Improving engineering education outreach in rural counties through engineering risk analysis,” in Journal of Professional Issues in Engineering Education & Practice; 2010; 136(4).

[50] K. Yelamarthi and P. R. Mawasha, “A pre-engineering program for the under-represented, low-income and/or first generation college students to pursue higher education,” in Journal of STEM Education; 2008; 9(3): pp. 5-15.