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STEM education and problem-based learning

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Introduction: STEM as a paradigm shift

One of the most significant current reforms of science education is implementing interdisciplinary science, technology, engineering and mathematics (STEM) subjects in middle and high schools because of its impact on increasing students’ interest in STEM professions in addition to increasing students’ twenty-first century skills (Asghar, Ellington, Rice, Johnson, & Prime, 2013). The new reform of science education aims to increase the professional careers of STEM subjects (Kuenzi, Mathews & Mangan, 2006; National Science Board, 2007). The benefits of STEM education are that it correlates real-world problems with the content being taught. The extended benefits from this relationship are that it increases students’ interest and motivation in STEM careers as well as avoiding questions about why they have to learn this subject (Asghar et al., 2013; Merrill & Daugherty, 2010). Many researchers are convinced that STEM education contributes to students’ acquiring skills in problem solving, critical thinking, collaboration, management, self-directed learning, communication, creativity and innovation, and analytical thinking, as well as a connection to real-world problems (Asghar et al., 2013; Capraro, Capraro & Morgan, 2013; Casteldine & Chalmers, 2012; National Science Board, 2007).

The aim of integrated disciplines is to demonstrate a paradigm shift from the separate subject approach to teach real-life problems (Capraro et al., 2013; Jonassen & Hung 2008) that require integrated knowledge from different disciplines (Dugger & Fellow, 2011; Merrill, 2009), and to solve the problems collaboratively in a constructivist approach (Mayer, 2004). In the past decade, there has been special interest in STEM education, especially when it is taught through effective
teaching strategies in order to prepare students for STEM professions. Several studies have produced estimates of considering PBL as the best strategy to teach STEM (Asghar et al., 2012), but there is still insufficient data for measuring to what extent using PBL strategy in teaching K-12 students STEM project can enhance their twenty-first century skills, which include critical, cognitive and collaborative elements. The main purpose of this chapter, therefore, is to argue and explain to what extent using PBL as a strategy enhances students’ twenty-first century cognitive and collaborative skills that are inherent in STEM education.

Interdisciplinary STEM

Science, technology, engineering, and mathematics (STEM) education is usually named as a meta-discipline. It is the creation of integrated knowledge across disciplines to form a new curriculum to be taught as a whole. STEM was first coined by the national science foundation as an educational term in the early 2000s.

STEM education has been defined as “a standards-based, meta-discipline residing at the school level where all teachers, especially science, technology, engineering, and mathematics (STEM) teachers, teach an integrated approach where discipline-specific content is not divided, but addressed and treated as one dynamic, fluid study” (Merrill, 2009, p. 49). STEM education gives opportunities to students to understand the world around them and solve real-world problems. According to the Organization of the Economic Co-operation and Development (OECD) report, productive individuals should have a high level of technical skills and also be independent, cooperative, and flexible in improving their qualifications (Hakkarainen, Paavola, & Lipponen, 2004).

In order to understand STEM, it is significantly important to understand the relationship between its disciplines. Science seeks consistency and understanding of the external world (NRC, 1996). There is a strong link found between science and technology to the extent that most individuals think that technology is applied science. The processes that are used in learning about science encompass exploring, discovering, or inquiring. The use of scientific method is the most important to apply science.

Technology has been defined as what is human made (Yakman, 2010). It is driven by human genius and creativity and offers an efficient and productive life to make the lives of people easier by solving problems. Engineering is the profession that needs study, experience, application, and knowledge of science and math in order to utilize economically the materials that could benefit the humanity (Mello, DiaBiasio, & Vaz, 2007–2008). The National Academy of Engineering supports technology and engineering literacy because of the strong relationship between the two disciplines (Dugger & Fellow, 2011). Finally, Mathematics investigates the patterns and relationships of sciences (AAAS, 1993), as explained by mathematicians today that mathematics is the study of patterns real or imagined, visual or mental, arising from the natural world or from within the human mind (Devlin, 1997). Mathematics is a common discipline that is used in many disciplines such as science, technology, and engineering not only for numbers, measurements, probability, but also for use of minimum formulas, precision and purity.

There are a number of ways that STEM can be taught in schools. The first option is to teach each discipline of STEM as an independent subject with no or little integration. This is known as S-T-E-M. The second way is to teach each of the STEM disciplines with emphasis on one or more subjects and this is referred to as SteM. Another strategy is to integrate the three disciplines into one discipline that can be taught. For example, robotics is an engineering project, but requires integration between science, technology, and mathematics. In this case, the engineering teacher will take responsibility in teaching the subject. However, the collaboration between teachers of the other disciplines is very important in teaching the subject. This is known as E→STM (Dugger & Fellow, 2011). Figure 29.1 illustrates the three types of interdisciplinary STEM.
Dugger and Fellow (2011) themselves recommend that the more comprehensive way is to integrate the four disciplines into each other as one subject. They contend that as there are technological, engineering, and mathematical contents in science, so the science teacher needs to take responsibility to teach this integrated content with the help and collaboration of other teachers.

Dugger and Fellow (2011) further emphasize that efforts should be taken in order to choose the best teaching strategy that suits STEM education. STEM requires hands-on methods, technological tools, equipment, and procedures to be used in creative ways to teach and learn authentic content and problems that meet human needs (Merrill, 2009). The STEM projects or concepts could be taught in different strategies such as models (Atkinson, Hugo, Lundgren, Shapiro, & Thomas, 2007), school-based STEM programs (Toulmin & Groome, 2007), distance learning (Demski, 2009), mentoring programs (Atkinson et al., 2007), and special STEM schools (Cavanagh, 2006). However, Asghar et al. (2013) argue that these methods have failed to address the nature of real-life STEM problems.

Problem-based learning

Problem solving has been defined as “a goal-directed sequence of cognitive operations” (Anderson, 1980, p. 257). Jonassen (2000) points out that the importance of problem solving is that it is the most important cognitive activity in everyday life. The national reports of the United States mentioned that current education is not adequate to prepare engineers and scientists in solving complex problems (National Academy of Engineers, 2005; National Science Foundation, 1996; AAAS, 2002; National Research Council, 2003).

Problem-based learning is a student-centered pedagogical approach that combines the inquiry approach and problem solving process (Etherington, 2011). The problems have a different variety of practices in problem-based learning; ill-structured problems or complex scenarios that can be adapted to students’ cognitive development (Du, de Graaf, & Kolmos, 2009; Ravitz, 2009; Jonassen & Hung, 2008). Learning with PBL occurs when students go through three steps: What do they know? What do they need to know? And how can they find out what they need to know?

There are some theoretical principles that support PBL which are constructivist process, metacognition, and cultural and social factors. The PBL theory is a constructivist theory as it requires learners to build their own understanding of new ideas. The constructivist process is contained in “What do they know? What do they need to know? How do they know?” In other words, explicit attention should be paid to students’ prior and existing knowledge, and the ability to construct new knowledge based on prior knowledge. Piaget (1954) described this cognitive process in three stages: assimilation, accommodation, and equilibrium, in which learners incorporate new experiences into existing experiences. The learner’s cognitive structure is thus modified in response to the environment, and achieves balance between what is being understood and what has to be understood. The co-constructed process in which individuals interact and work collaboratively in solving problems is internalized by the individual and becomes part of the student’s cognitive development (Vygotsky, 1978). A large and growing body of literature
has revealed that there are three types of learning included in PBL models: cognitive learning, content learning, and collaborative learning (Hewlett Foundation, 2010; de Graaff & Kolmos, 2003, 2007) and Figure 29.2 illustrates these three elements’ relationship with PBL and STEM.

Figure 29.2 shows that cognitive learning focuses on critical thinking, creativity, and innovation skills while collaborative learning focuses on collaboration, self-direction, and communication skills. Finally, content learning focuses on the integrated knowledge through STEM disciplines, use of technology, and connection to real life which lead to fine outcomes, such as, higher-order thinking skills.

Yelland, Cope, and Kalantzis (2008) assert that this constructivist approach not only promotes communication and collaborative skills, but also fosters reflection from multiple perspectives. This in turn enhances students’ critical thinking skills where students analyze problems, apply deductive and inductive processes to understand problems, and find creative alternatives to the problems (Lai, 2011). Students in all STEM subjects are granted opportunities to use their prior knowledge and new knowledge to reason intellectually in collaboration with their peers in small groups (Capraro et al., 2013).

**Relationship between PBL and STEM**

STEM education by its nature requires ill-structured problems that are connected to the real world. Prominent research has been done on the nature of the problems used and their impact on the students. The results from these studies have stipulated that the more complex the problems are, the more skills students gain (Capraro et al., 2013; Russell, Hancock, & McCullough, 2007; Lopatto, 2004). According to Jonassen and Hung (2008), problem-based learning strategy requires ill-structured and complex problems with a moderate degree of structure that are contextualized to real-life in order to engage and challenge students, and which enable them to adapt their cognitive development and prior knowledge.
Furthermore, Barrows (1986) developed a taxonomy that categorized PBL into six categories in three levels by using two variables. The first variable is self-direction that varies from the teacher-directed, to student and teacher-directed, and to student-directed. The second is the problem structure that differs according to the complexity of the problem; well-structured, between ill-and well-structured, and ill-structured. Figure 29.3 illustrates this PBL taxonomy.

Harmer and Cates (2007) mentioned that pure PBL is the best pedagogy applicable to teach authentic real-world problems that require interdisciplinary STEM. PBL models require students’ active engagement in using knowledge and delving deeply in finding information about the ill-structured problem, then, synthesizing and following metacognitive processes to solve the problems which result in the use of higher-order thinking skills (Capraro et al., 2013; Liu & Bera, 2005).

Cognitive, content, and collaborative learning cut across PBL

Hakkarainen et al. (2004) propose a metaphor for learning called a knowledge-creation metaphor. This approach sets a guide for new strategies of teaching and learning that promote cognitive learning, collaborative or social learning, and the challenges and innovations of integrated knowledge in a specific content (Nielsen, Du, & Kolmos, 2010). Many researchers agree that there are three types of learning which occur in the implementation of PBL models and practices which are cognitive learning, collaborative learning and content knowledge (Du et al., 2009; Ravitz, 2010).

Cognitive learning focuses on ill-structured problems, the process of solving complex problems, and developing students’ critical thinking, creativity, and motivation skills through application of this approach. Critical thinking has been defined as “the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action” (Scriven & Paul, 2007, p. 1). It has been
referred to as metacognition or the process of thinking about thinking (Tempelaar, 2006). It is a mental habit that requires students to use their higher-order thinking skills in synthesizing, analyzing, and evaluating information to solve problems and make decisions (Scriven & Paul, 2007; Tempelaar, 2006). Critical thinking is described as one of the abilities that students can acquire in the short term. The individuals usually behave more or less not only by the ability, but also by tendencies and this aspect is called critical thinking dispositions (Ennis, 1986). Critical thinking dispositions takes a long time to be acquired and is essential for learners to have practice in thinking critically about an issue (Norris, 1985). Forawi (2012) believes that critical thinking dispositions can be developed in students by applying intellectual standards to the elements of reasoning. However, there are many arguments that teachers do not know how to teach critical thinking skills in their instructions or the way to integrate critical thinking skills in teaching strategies. Broadbear (2003) contends that teachers have in-depth information about content knowledge, but generally, lack the pedagogical content knowledge that is based on Shaulman’s idea.

Moreover, most philosophers describe creativity as a skill that enables individuals to produce something new and valuable, and analyze situations in a creative way (Sternberg, 2010). Psychologists such as Vygotsky and Guilford have emphasized the importance of developing creativity in children in order to change the future (Beghetto, 2010). Many educators suggest that engaging students in tasks that foster them to think creatively can help their cognitive, emotional, and social development (Sawyer, 2006) in addition to the self-direction skills that they acquire (Sternberg, 2007).

Many studies suggest that teachers need to know how to integrate creativity in their teaching practices (Jacucci & Wagner 2007). Dewey (1934) pointed out that teachers can facilitate and support students to think creatively but cannot teach them creativity. Kaufman and Sternberg (2007) stated that creativity is relevant to the process of solving the problem or task that is created. Barry and Kanematsu (2008) suggested that teachers should focus on the interdisciplinary approach and multisensory element in creating a learning environment. Piggot (2007) believes that mathematics as a subject forces students to think creatively in solving problems. One of the factors of science and engineering education is that they make students change the world by exploring new ideas from the existing materials in the environment. Most researchers recognized the combination of the cognitive skills, dispositions, and environmental factors in achieving creativity (Sternberg, 2006; Torrance, 1997; Treffinger et al., 2002). Cognitive skills related to creativity include the ability to identify problems (Sternberg, 2010; Torrance, 1997), generate ideas and think of alternatives (Treffinger et al., 2002), and solve problems (Torrance, 1997).

Creative learners tend to have the intrinsic motivation in learning and thinking of new ideas (Sternberg, 2010). Motivated learners are seen as willing to take intellectual risks to fall into mistakes and learn from them, and have self-efficacy in creating new ideas that face resistance from society (Beghetto, 2010; Sternberg, 2006, 2010; Treffinger et al., 2002). However, environmental and cultural factors play an important role in limiting students’ thinking about the new ideas (Runco, 2004; Sternberg, 2006). In previous studies, it has been mentioned that PBL has a positive impact on students’ motivation in solving a specific problem (Tarhan & Acar, 2007; Kelly & Finlayson, 2009). For instance, research has indicated that students still encounter some difficulties in solving mathematical problems and in relating their learning to real-life (National Mathematics Advisory Panel, 2008). Students are unable to engage with mathematical concepts and may not be interested in such lessons as the problems are well-structured and not related to real-life. In addition, some students may be unmotivated and less confident to direct their learning route, which increases dependency on teachers. In such contexts, using technology can ignite students’ interest to learn about other disciplines (Capraro et al., 2013), and increase motivation.

One of the most important notions of constructivism is real-world tasks (Woo & Reeves, 2007). Meaningful learning occurs in considering knowledge of content as a starting point that
is required to solve real-life problems by applying metacognitive process (Hmelo, Gotterer, & Bransford, 1997) and connecting this information and knowledge to solve real-life problems (Harris & Grandgenett, 2002). STEM focuses on the depth of knowledge in terms of communicating new ideas to prior knowledge, connecting knowledge to real-life, integrating knowledge in solving problems, and reflecting on the strengths and limitations of the solutions (Capraro et al., 2013). By applying this type of learning, students will be able to communicate their ideas, integrate knowledge across disciplines, and use technology to facilitate their learning.

PBL as a strategy is a top-down process that requires students to solve problems, analyze, synthesize, think critically, and communicate knowledge from several disciplines which has been promoted by constructivism (Terhart, 2003). Accordingly, teachers take the responsibility to guide, facilitate, and coach students in order for them to acquire and improve the top-level skills (Slavin, 2012). Metacognition is described as a path to learning (Bruning, Schraw, & Ronning, 1998). It is defined as the executive control of thought that involves monitoring, self-regulation, and awareness (McLeod, 1997; Kuhn & Dean, 2004). Students who use metacognitive process are able to use this information in new situations as they can remember it longer (Storbel & Barneveld, 2008). Integrated knowledge is a method of using knowledge that is embedded in STEM education which requires students to apply the metacognitive process. One of the goals of the interdisciplinary curriculum is emphasizing that real-world problems cannot be separated into isolated subjects (Capraro et al., 2013).

The role of technology in education is also an important factor that cannot be ignored (Almekhlafi & Almekdadi, 2010). Technology can provide students with a large amount of information and be set as a tool to control their learning process (Lam & Lawrence, 2002). Extensive research studies have explored the positive impact of using technology with students in teaching and learning processes (Almekhlafi & Almekdadi, 2010). Sherry, Bilig, Jesse, and Acosta (2001) recommend that teachers should guide students in using metacognitive skills, inquiry of learning, and problem-solving process as they integrate technology into their academic content areas. Becker and Ravitz's (2010) study reported that using technology in classrooms as a tool to facilitate learning is strongly related to the constructivist views and practices in its compatibility with student-centered approaches. Anderson and Maninger (2007) extol the changes in students’ abilities, self-efficacy, and beliefs in using technology as a tool in learning. Furthermore, many researchers investigated different aspects of integrating technology in learning that allow students to learn more in less time and allow them to focus on real-world scenarios and problems (Capraro et al., 2013; Zhao, 2007; Gulbahar, 2007; Anderson & Maninger, 2007; Abbit & Klett, 2007). Collaborative learning is the ability of students to work on a task collaboratively, which develops students’ collaborative and self-direction skills. Vygotsky (1978) focused on the role of social interactions between students, language and culture in the learning process (Fosnot, 2005; Woo & Reeves, 2007). Dillenbourg, Baker, Blaye, and O’Mally (1996) distinguished the difference between cooperative learning and collaborative learning. Cooperative learning is when each learner is working in parallel on separate portions of specific tasks while collaborative learning is when students are working together on the same task. Collaboration may divide the cognitive process into intertwined layers (Lai & Viering, 2012). Thus meaningful learning occurs when students work collaboratively in small groups (Veennman et al., 2005; Webb, Farivar, & Mastergeorge, 2002). Social constructivists expound the interactions of students with their peers in solving authentic and real-life problems (Azzarito & Ennis, 2003). Boxtel, Linden, and Kanselaar (2000) mentioned that collaborative learning allows students to reflect on their work, provide explanation, elaborate and recognize their knowledge. Collaborative learning includes many sub-skills that include coordination, problem solving, decision making, communication, and conflict resolution. In addition, there are many forms of communication when students
work collaboratively such as providing explanation, asking questions, and responding to others’ requests (Gillies, 2003; Webb, Farivar, & Mastergeorge, 2003). A clear example demonstrated in a study by Kazak, Wegerif, and Fujita (2014) that shows that students’ use of dialogic talk in combination with use of technology leads to a shift from intuitive reasoning to probabilistic reasoning.

Self-direction is the responsibility that learners take in directing their learning and is usually a personal attribute of learners (Brockett & Hiemstra, 1991). Brockett and Hiemstra (1991) have viewed self-direction in learning as an instructional process and a personal characteristic of learners. Brookfield (1986) stated that true self-directed learning comes from the inner transformation of schemes with the attention to self-discipline. Tough’s (1971) research found that self-directed learning is a commonplace event in the life of learners. Self-directed skills tend to occur in constructivism classrooms where students work collaboratively in solving real-life problems and have the intrinsic motivation to assume responsibility in directing their own learning.

Conclusions and implications

This chapter has argued that STEM education is best taught through the problem-based learning approach that can enhance students’ cognitive and collaborative skills. The chapter has shown that the most comprehensive way of teaching interdisciplinary STEM is the third method that focuses mainly on one discipline with integration with the other disciplines. For example, the real-world engineering project (robotics) that focused on engineering mainly, and then integrated with other disciplines, such as maths, science, and technology. Another example is mathematical modeling through its transition, processes, and competencies. Also, Capraro et al. (2013) described the STEM disciplines using the parts of the human body as analogies: science is the musculoskeletal system, technology is the hand, engineering is the brain, and mathematics is the heart and blood. Thus, it is apparent that these disciplines are interrelated with each other in teaching real-life projects. It is impossible to manufacture supersonic aircrafts, robots, space shuttles, submarines, cell phones, or tunnels without knowledge of science, technology, engineering, and mathematics. In this light, PBL provides real-life experiences for learning that adopt a higher-order of thinking.

Through exploration of the literature, problem-based learning is found to be a better strategy than project-based strategy in teaching STEM related curricula and activities. According to Barrows’ PBL taxonomy, the pure problem-based learning requires students’ self-direction in solving ill-structured problems (Hung, 2011). In teaching STEM projects, students solve ill-structured problems that are related to real-life. The three types of learning that occur in PBL are cognitive learning, collaborative learning, and content knowledge which have been proven to enhance students’ skills (Du et al., 2009; Kolmos et al., 2009; Ravitz, 2010). In this sense, Collaborative learning plays an essential pedagogical tool within PBL that develops students’ collaborative, self-direction, and communication skills. To sum up, this chapter supports the idea that teaching STEM projects should focus on real-life task built on constructivism. Vygotsky (1978) also emphasized the role of the co-constructed process where the learners interact and collaborate in solving problems. Constructivism, which is the backbone of PBL, shapes the cognitive process where students incorporate new experiences to their existing experiences (Piaget, 1954) and become users of information in a student-centered environment.

These arguments concur with Nielsen, Du, and Kolmos (2010), who assert that the requirements of globalization demand new trends in PBL models and practices such as interdisciplinary projects. Vast amount of literature has reiterated that learning PBL–STEM can improve students’ cognitive, content, and collaborative skills, and consequently influence thinking processes across discipline borders and shape students’ careers (Russell et al., 2007). Many studies have also promoted the important role of technology as it helps students in using knowledge, delving deeper into
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the content, and developing reasoning skills (Dani & Koenig, 2008). In order to contribute technology to the design and implementation of STEM-PBL, and to make the learning process more effective, technology has two roles to fulfill. First, technology education should be integrated into STEM (Capraro, 2009), and second, technology should be used to foster STEM PBL (Cifuentes & Ozel, 2009). Moreover, previous studies have acknowledged the important role of PBL as a strategy to teach integrated subjects in developing students’ skills such as critical thinking, collaboration, creativity, management, communication, and motivation skills (Casteldine & Chalmers, 2012; de Graaff & Kolmos, 2003, 2007; Du, 2006; Du & Kolmos, 2006; Evensen & Hmelo, 2000).

There is a coherent structure in STEM instruction through the common core standards used that can serve as the benchmark for accomplishing teaching STEM disciplines through implementing the STEM project. However, additional professional development for teaching STEM is highly recommended, as the onus is on teachers to design learning experiences that guide students’ learning to identify the knowledge and skills needed. Therefore, it is highly recommended that teachers attend professional development programs to obtain training in the way of integrating critical thinking into their teaching practices.

References


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