Chapter 2

Framework for the Development of a Study on Authentic Problem Solving Skills in K-12 Grades

SUSHEELA SHANTA
School of Education, Virginia Tech
Blacksburg, Virginia 24061, USA

Abstract

Collectively identified as one of the 21st century skills, critical thinking and problem solving skills (CT and PS) involved in solving authentic design problems are not assessed in traditional science and mathematics standardized testing or in most technology education K-12 classrooms. 21st century learning outcomes are realized when students are able to gain deep understanding of science and math concepts, and, use the content and practices of these disciplines with the content and practices of technology and engineering to solve problems situated outside the classroom. For this to occur, integration of the disciplines in the instructional approach is essential (NRC, 2009; Sanders, 2012). Researchers have argued that the integrative STEM education (I-STEM ED) pedagogical approach (with its roots in technology education) promotes active learning through student discovery of using science and mathematics content and practices in novel situations.

This paper presents the results of the literature review conducted to develop a framework for characterizing and defining CT and PS skills. Specifically, this paper is organized around the following four themes: 1) the foundations of STEM education and theories of learning that underpin the I-STEM ED pedagogical approach, 2) the need for CT and PS skills among students to meet the 21st century educational goals, 3) the relationship of CT and PS skills to the T/E DBL approach used in I- STEM ED, and, 4) gaps in the research focusing primarily on studies within the 21st century. Furthermore, a potential framework for a rubric for assessing CT and PS skills is proposed.

The Problem

The shortfall in the intended outcomes for students' achievement of the implied higher order thinking skills, characterized by one of the five C's of the 21st century skills – critical thinking and problem solving (P21, 2015a), is a focus of STEM education reform. Specifically, outside the confines of traditional classroom settings, students are not able to recognize, recall, and utilize the science and math content needed for solving authentic design-based problem solving (Song, et al., 2016).

One reason for this inability to recognize, recall and utilize the needed science and math content could be that students are not learning and practicing the utilization of multidisciplinary content in the context of designing solutions to authentic problems. The technology education (Tech-ED) framework has traditionally been geared toward student learning through the content and practices of technological and engineering design. However, not all students are able to access Tech-ED coursework, and not all Tech-ED teachers are prepared with the science and math content knowledge to do justice to the pedagogical approach needed to integrate the disciplinary content areas and practices (Wells, 2010). The practice of an integrative science, technology, engineering and mathematics education (I-STEM ED) pedagogical approach is defined as:

> the application of technological/engineering design based pedagogical [T/E DBL] approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels. (Wells & Ernst, 2012/2015)

Viewed from this design-based learning context, the absence of such pedagogical practices presents a key problem for promoting student development of higher order thinking skills necessary for critical thinking and problem solving (CT and PS) in the context of the 21st century needs. As Wells (2008) explains, I-STEM ED "fosters a blended pedagogical approach and establishes the curricular foundations that have long been supported by cognitive research" (p. 11).

The lack of research to support the benefits of T/E DBL as a signature pedagogical approach of integrative STEM education, for "conceptual attainment" (Zuga, 1995, p. 67) and "problem solving" (Zuga, 2000, p. 2) skill development as outcomes of technology education hinders the promotion of more widespread use of this integrative pedagogical practice (Cajas, 2000; Kolodner, 2000; Zuga, 2000). To investigate the benefits of the I-STEM ED pedagogical approach in promoting the development of CT and PS skills it is essential to identify those student abilities that contribute to CT and PS skills. Furthermore, an assessment instrument and scoring rubric would be required to quantify those abilities.

A literature review was conducted to investigate the pedagogical framework within which development of students' CT and PS skills are situated. This paper is organized around five distinct areas: 1) foundations of STEM education, 2) learning theories underpinning I-STEM ED, 3) the pedagogical approach of I-STEM ED, 4) development of CT and PS skills, and 5) the relationship of CT and PS skills to the T/E DBL approach used in I- STEM ED. Results of these investigations are summarized, followed by conclusions and implications regarding future research on this topic.

Foundations for Integrative STEM Education

The rapid pace of change, the complexity of human problems, and the ease of global access to technologies and human resources have created the demand for education to help develop the next generation of STEM literate workforce (Friedman, 2005; NAE & NRC, 2014). Efforts to reform science and mathematics K-12 education to meet the challenges of the coming decades have been ongoing since the 1960s. The individual disciplines in STEM – science, technology, engineering and mathematics have distinct pedagogical approaches and educational goals that address literacy in those disciplines (NGSS Lead States, 2013; ITEEA, 2000/2002/2007; NCTM, 2000). Despite these reforms, the way in which STEM education has been interpreted and practiced in K-12 has been a "siloed" (NAE & NRC, 2009, p. 12) approach which has resulted in students' lack of ability to utilize their knowledge in real world applications, sometimes called transfer of learning (Wiggins & McTigue, 2005). Furthermore, STEM education has been largely interpreted as an emphasis on science and mathematics education in most classrooms, with those subjects being taught without any relationship to the other disciplines (Wells, 2013). With the lack of technology education programs in most schools, students do not even experience the interconnectedness of the STEM disciplines in the technological design applications of the curriculum (NAE & NRC, 2009).

More recently, engineering design has been introduced within some science and technology education classrooms. In *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (NAE and NRC, 2009) a multidisciplinary committee of experts noted that engineering is a way to increase student achievement in technological literacy, increase student achievement in science and mathematics literacy, and also, to act as a catalyst in integration of STEM education in K - 12 grades. Uniform standards for engineering education in K-12 are not adopted by all states due to overburdened curricula in secondary education, and the lack of teacher preparedness for teaching an engineering curriculum in K-12 (NAE & NRC, 2009). Instead, science, technology and mathematics curricula have included design instruction (ibid). *A Framework for K-12 Science Education* (NRC, 2011b) created a new directive among science educators when it announced that the teaching of engineering concepts would be a part of the Next Generation Science Standards (NGSS). However, as stated before, these approaches are limited by teacher knowledge and preparedness for teaching engineering design within their disciplines (Wells, 2008; Zubrowski, 2002).

Literacy as defined within science, technology and mathematics is the ability to understand information or claims in the context of the disciplines, evaluate the validity of the same, and, communicate evaluations and predictions with a vocabulary that is consistent within that discipline (NGSS Lead States, 2013; NCTM, 2000). This definition inherently separates the content and practices of each of those four disciplines in STEM, and is not representative of authentic or real world situations where it is necessary to devise solutions or problem-solve within the intersections between the disciplines (Sanders, 2012; Pope, Brown and Miles, 2015). For students to succeed in college or in the workforce, they need to be able to function in the continuum of the four disciplines, and this necessitates STEM education to be intentionally integrative in its approach (Huber & Hutchings, 2004).

Learning Theories underpinning the I-STEM ED pedagogical approach

Learning is a cognitive process that involves conceptual growth and reasoning. External input is processed in the brain by encoding and storing information in long term memory in a meaningful manner from which it can be recalled and utilized when needed (Greeno, Collins, &

Resnick, 1996). While this is a simplistic explanation, the processes involved are complex and require more intentional teaching and learning.

A widely-used model of the process of learning is that human senses receive new input, which are held in a sensory register for a fraction of a second and passed on to working memory. In working memory, the information is processed and immediately stored in long-term memory or lost. Information is stored in long-term memory, only if it has some strong emotional associations for the learner or makes sense to the learner and has a connection to some previously stored information from past experiences (Bransford, Brown & Cocking, 2000; Brown, Collins & Duguid, 1989). Furthermore, learners' construction of knowledge is linked to the activity, context and culture in which it is learned (Brown, Collins & Duguid, 1989).

Although most learning occurs in a collaborative or social context, such construction of knowledge requires an individual to be engaged as the sole constructor of his/her knowledge, uniquely related to his/her previous knowledge. Retrieval of stored information repeatedly strengthens the interconnectedness of stored information and its future recall at appropriate times is enhanced. This intentional teaching and learning process, where information is repeatedly retrieved and used in different ways, supports the development of cognitive connections required for integration (Huber & Hutchins, 2004). In alignment with constructivism as originally proposed by Jean Piaget (1968) and later supported by cognitive science research (Bransford, Brown & Cocking, 2000), it becomes the responsibility of educators to design instruction in a manner that enhances students' knowledge construction in an integrated and sense-making manner. Furthermore, repeated and consistent experiences are needed to enhance the robustness of interconnectedness of concepts, and create habits of mind.

The I-STEM ED pedagogical approach promotes active learning through student discovery of using science and mathematics content and practices in designing solutions to identified problems, and active construction of understanding by doing (Wells, 2017, 2016b). Within engineering design, the predictive nature of designing a solution and testing the model or prototype in an iterative fashion, are opportunities (with instructional guidance) to refine one's understanding due to inconsistencies observed known as cognitive dissonance (Festinger, 1962; Puntambekar & Kolodner, 2005). The central tenet of education is to increase students' understanding, and many researchers have argued that the T/E DBL approach is effective in increasing students understanding through such cognitive dissonance (Cajas, 2001; Wells, 2010; Puntambekar & Kolodner, 2005; Barlex, 2003). Although there is an acknowledged lack of evidence to support this claim (Zuga, 1995), there is potential for cognitive growth in the I-STEM ED pedagogical approach.

Despite recognition of the need for integration, historically the focus has remained on increasing students' proficiency in the individual disciplines. It has only been in the last decade that there has been a recognition that US students' performance in assessments outside the classroom lags behind (Pope, Brown & Miles, 2015). Researchers have noted that using an instructionally independent approach, or the silo approach, to teaching the disciplines has resulted in students' lack of success in science and math performance outside the classroom (NRC, 2009). When students understand and experience the interconnectedness between the disciplines, their performance and literacy are likely to improve (NRC, 2009; Drake & Burns, 2004). The intentional integration of the content and practices of the disciplines as a pedagogical approach helps develop STEM literacy, rather than focusing on literacy in the individual STEM disciplines (Sanders, 2012). Effective use of grade-appropriate science, technology, engineering & mathematics disciplinary concepts and practices in designing and implementing solutions to authentic problems would help provide meaningful experiences for students to understand the relevance of learning in the real world. The *Standards for Technological Literacy* published in 2000, and revised again in 2002 and 2007, promoted the integration of various content areas using technological and engineering design as the vehicle to deliver multiple disciplinary content in an engaging and integrative manner.

The widely accepted definition for I-STEM ED suggests the *intentional* teaching of content and practices of science and mathematics through the content and practices of technology and engineering education (Wells & Ernst, 2012/2015).

T/E DBL as the pedagogical approach of I-STEM ED

The pedagogical approach in I-STEM ED supports knowledge construction through intentional hands-on experiences to engage students to achieve minds-on learning outcomes (Wells, 2017, 2016a). The intentional design of learning experiences within I-STEM ED addresses deeper learning through scientific inquiry, engineering design, predicting and testing, all encapsulated in the T/E DBL pedagogical approach. Within the existing school infrastructure and curriculum framework, the T/E DBL approach is best suited to Tech-ED courses and programs. However, these courses are in most states electives, lack importance in terms of graduation or college admission, and lack teacher preparedness to teach the needed science and math content within the T/E design-based approach.

As John Dewey (1910) noted and others have since confirmed, hands-on experiences are better than learning by hearing or through demonstrations (Wiggins & McTighe, 2005; Felder & Brent, 2016). However, the interpretation of hands-on learning for instructional purposes has primarily been project-based learning (P_jBL inclusive of technology education classrooms. Specifically, students are provided an end-goal for a project, some criteria and constraints, instruction on how to accomplish the end-goal, detailed instruction on the hands-on aspects, and informed that assessment is directly tied to the various parts (what one can see, hear, and touch) of the project.

As Felder and Brent (2016) note, the PjBL approach is teacher-centered and does not imply learning has occurred. For learning to occur, not only do the students have to engage in the hands-on activities, but they have to be "caused" to learn (p. 6). One method is to engage students in learning experiences that are inquiry based and embedded in a challenge that is relevant to their lives. To successfully design a solution, students need to research and learn the content areas related to the embedded problem, design a solution, and build and test a prototype or a model. Researchers have also found that learning improves when the content is relevant to students' lives (Drake & Burns, 2004; Fennema, 1992), and this can be satisfied with the use of relevant and appropriate authentic design problems. One instructional model named PIRPOSAL© for T/E DBL (Wells, 2016b) exploits "the full spectrum of complex learning processes" (p. 15) that are associated with the definition of the I-STEM ED pedagogical approach.

The T/E DBL approach engages students in a design challenge that is central and the focal point for a "convergent and divergent" questioning process within which students engage in learning and designing (Wells, 2016b, p16). Design, a process that is inseparable from innovation, is a collaborative activity within which a group of people tackle an ill-defined (or authentic) problem that is constrained by resources available and the constraints of real-world conditions. Most real-world problems are ill-defined and can have multiple solutions (Ormrod, 2012). The optimal solution involves the optimization of constraints and benefits. The

ITEA/ITEEA (2000/2002/2007) regards design as "an iterative process that produces plans by which resources are converted into products or systems that meet human needs and wants or solve problems" (p. 237).

The design challenge in the T/E DBL approach is central to students' learning experience. Construction of knowledge occurs within the relevant context of the design challenge and within the culture of peer-to-peer questioning and researching in a collaborative environment, and this is how students learn (Brown, Collins & Duguid, 1989; Bransford, Brown & Cocking, 2000). This student-centered instructional style has been found to be superior to the traditional teacher-centered instructional style (Felder & Brent, 2016). Using a process of 1) identifying and defining the problem that must be solved, 2) defining criteria for the solution, and 3) identifying the disciplinary content areas that relate to the problem, students engage in a collaborative process of questioning, researching and ideating to design, build, evaluate and re-iterate until an acceptable solution is created. Instructional strategies used in the T/E DBL pedagogical approach are intentionally designed based on Gagne's events of instruction (Gagne, Wagner, Golas, & Keller, 2004) to promote students' knowledge construction in the procedural, declarative, schematic and strategic knowledge domains (Wells, 2016c). The iterative and repeated design process requires students to reflect on their existing knowledge in all relevant subject areas in order to construct new knowledge and this is an important aspect of developing habits of mind (Jonassen, 1997).

From the perspective of a cognitive approach, the four types of knowledge constructed by students from the (intentionally placed) cognitive demands of design-based problem solving are:

- declarative knowledge, which includes definitions, concepts and principles of a subject,
- procedural knowledge, which is the practice used within the subject or discipline,
- schematic knowledge, which is the reasoning and relationship between concepts, and,
- strategic knowledge, which is knowing the appropriate utilization of concepts (NAGB, 2009; Shavelson, Ruiz-Primo & Wiley, 2005).

These types of knowledge are hierarchical and reflect deeper learning when students are able to exhibit the interconnections between concepts and disciplines and demonstrate the use of the knowledge in developing a solution to the posed design challenge (Webb, 1997). However, isolated experiences of T/E DBL where students may learn in this manner in a Tech ED class will not achieve the goal of developing habits of mind and habits of hand. As discussed previously, Tech-ED is not mandatory as part of the K-12 curriculum (for graduation) in most states. Only repeated experiences in T/E DBL within an integrative STEM educational program would help students develop these habits, and most students do not have opportunities for these experiences.

The potential of I-STEM ED for improving student achievement

The Partnership for 21st Century Skills (P21) argues that for students to succeed in college and careers in the 21st century, development of five essential skills are necessary – 1) critical thinking and problem solving, 2) communication, 3) collaboration, 4) citizenship and 5) creativity in innovation (P21, 2015a). In addition, the fast changing technological environment of the 21st century requires students to be competent in transferring their learning to new situations and new problems (NRC, 2012b). These competencies require interconnected disciplinary content knowledge, and knowledge of how, why and when to apply this knowledge to answer complex questions or solve problems (ibid). In a recently published info-graphic by The

Chronicle of Higher Education (http://results.chronicle.com/C2C-IG-2017), the most important skill employers look for in new employees, is the ability to make decisions (to problem-solve) in a complex multi-faceted technical environment. Making decisions in a multifaceted technical environment implies that workers should have not only technical skills in their discipline, but also be able to recognize the content of other disciplines, evaluate the usefulness of the identified content, and be able to create a strategy for making an informed choice on how to proceed. Without the knowledge of interdisciplinary content areas and knowledge of how, why and when to apply this knowledge, this is hard to do. Problem solving and critical thinking go hand-in-hand, where achieving the end-goal or solving the problem requires decision-making about disciplinary content to be used, discarding irrelevant information, devising a strategy and evaluating progress (P21, 2015a).

In the traditional Tech-ED classroom, design skills are assessed through achievement of competencies specified in select Career and Technical Education (CTE) courses, where disciplinary content in science and math are not the focus of instruction even in the STEM cluster. For example, in Virginia, the competencies listed in the CTE (2015) website for most of the courses start with workplace readiness skills, identified as: 1) personal qualities, leadership and people skills, 2) professional workplace skills, 3) examining aspects of industries, 4) historical overview of technology or engineering, and, 5) knowing the design process. In some of the engineering courses, managing real-world problems is explained as researching the context of a local problem and interviewing professionals on the various aspects of the problem (CTE, 2015). While these competencies are only the bare minimum required, it is worth noting that there is a lack of focus on solving authentic or real-world problems. Therefore, as traditionally implemented, the Tech-ED classroom is an opportunity for students to experience P_jBL, but not fully utilized as an opportunity to promote the higher order thinking needed in solving authentic problems.

In the traditional secondary educational classroom, the required core subjects of science and math are taught separately, and assessed using standards of learning assessments. Therefore, students with high scores in their science and math assessments, and high levels of proficiency in the competencies measured by the CTE courses, do not develop the interdisciplinary literacy that is necessary for real-world problem solving in situations outside the confines of their classrooms. The lack of integration skills hinders critical thinking when a problem solver is engaged in a multidisciplinary context and faced with an authentic problem. An example of such a situation is evidenced by the poor performance of students in assessments that are not within the confines of the classroom, such as the PISA and the TIMMS.

In the report on Discipline Based Education Research (DBER) (NRC, 2012a), the board on science education and the division of behavioral and social sciences and education summarized their recommendations regarding future directions of DBER. Included in this report is the recommendation for more studies on the K-12 students' transition to college to better understand the acquisition of important interdisciplinary cross-cutting concepts in STEM their influence on retention and persistence of students in the STEM disciplines. Furthermore, with respect to students' success in college especially in STEM disciplines, students switch out of these disciplines due to their inadequate high-school preparation for challenging math or science courses (Seymour & Hewitt, 2000, Haag, Hubele, Garcia & McBeath, 2007). Among other reasons for students' failure to persist in college STEM programs, Haag, et al. (2007) note that students' under preparation is caused by deficiencies in content and domain specific depth of knowledge, and lack of students' skills and habits in problem solving within science and mathematics topics (p. 932). Students' SAT scores and high-school standardized test scores do not reflect these types of deficiencies.

In an integrative STEM education program, all five of the 21st century skills mentioned before are learned and practiced within the context of the T/E DBL pedagogical approach. Students learn science and math concepts and practice their utilization in authentic problem-solving through the content and practices of T/E DBL. The T/E design challenge is appropriate for students to work together in a collaborative manner, with the teacher facilitating and providing guidance on teamwork skills. Intra-team communication is inherently essential and once again, the teacher helps students learn better ways to communicate with each other. External communication involves presenting the solution using visual presentations (posters, PowerPoint presentations), audio-visual (by making oral presentations or video presentations), and in writing by preparing reports and abstracts. Students are challenged to create unique solutions by engaging in friendly competition with their peers. Citizenship, which is a recent addition to 21st century skills, is addressed by having students interact with the connected computing technology in a responsible and reflective manner. Critical thinking and problem solving are addressed by having students grapple with complex criteria within the design context, to make decisions about the selection of relevant information and processes. Through the T/E DBL pedagogical approach, educators can help students learn the 21st century skills and "help students construct scientific understanding and real-world problem-solving skills" (Fortus et al, 2004, p. 1082).

By introducing the engineering design requirement in science and math standards, there has been an attempt to include the 21st century skills in every student's experience (NGSS Lead States;2013; NCTM, 2000). However, without assessment strategies for all these skills within the curriculum, there is no mandate for instruction to focus on teaching all these skills. Furthermore, including engineering design within science and mathematics instruction only introduces students to the design process without experiencing the integrative and inter-disciplinary approach embedded in I-STEM ED.

Characterizing Problem Solving

Researchers agree that problem solving is a decision making process (Reeff, 1999; Hayes, 1989; Martinez, 1998). Explicitly, problem solving is a goal driven process that requires recognition of the nature of the problem, identification of the end-state that implies success, creation of a strategy to go from the current-state to the end-state, execution of the strategy and adaptation of changes in strategy based on difficulties encountered along the way (Martinez, 1998; Hayes, 1989).When a problem is based in a real world context, the recognition and understanding of the problem in a solver's perception is key to devising a process to solve the problem, and this implies that no two authentic problems can be solved using the same knowledge or exact process (Reeff, 1999).

Not all problems are the same, specifically the two types may be characterized as: 1) well-structured, where all information needed to solve the problem are provided, and, 2) ill-structured, where there are many unknowns, many conflicting goals and multiple approaches to solve the problem (Jonassen, 1997). Well-structured problems are typical of problems practiced and assessed in the traditional science and mathematics classrooms. The other, ill-structured problems, which are typical of real-world situations, are much like what professionals see in the workplace. Solving such problems require a multiple disciplinary approach, often have multiple conflicting or vague goals, and not all information is even known. In the engineering educational setting, a design challenge, which will be referred to as an authentic problem in this study, with or without model making, is closer to the ill-structured end of the spectrum of problems (Heywood, 2005). It is important to know the process involved in solving such problems in order to develop an effective assessment of students' PS skills.

For solving authentic problems, methods can be algorithmic or heuristic or a combination of both (Martinez, 1998; Jonassen, 2000; Ormrod, 2012). Algorithmic methods are typical of mathematical problem solving in the context of a classroom, where students learn step-by-step procedures on how to work out factoring for quadratic functions or long division. Heuristic methods are more like general strategies or rules involved in an engineering design-based iterative problem that can only be solved through execution and testing. While algorithmic methods are not useful in authentic problem solving, general heuristics alone are also not reliable in authentic problem solving without deep understanding of the content areas within which a problem is embedded (Perkins & Solomon, 1989). In an authentic design problem situated in the context of science and mathematics, heuristics may help in creating the general strategies for solving the problem, but algorithmic methods may be used when it comes to utilizing specific mathematics and science knowledge to solve the problem. Furthermore, frequently practiced and accessed pathways to stored content in long-term memory help solvers with recognition of content areas relevant to the problem, and to think and reason forward in order to evaluate the results of any particular action to progress logically towards a solution (Perkins & Solomon, 1989).

From a cognitive perspective, the mental processes involved in problem-solving are based on knowledge and prior experiences of the solver (Ormrod, 2012; Newell & Simon, 1972). The prior knowledge is stored in long term memory and information gleaned from the problem are stored in short term or working memory. The latter has limited capacity and therefore can become overloaded during problem solving. This cognitive overload can hinder the solver's ability to successfully complete the solution. Therefore, the science, mathematics and engineering methods of problem solving recommend identifying and writing down (symbolically and visually) identified information (Heywood, 2005; Jonassen, 1997; Jonassen, Stroebell & Lee, 2006). This relates to the first phase of solving an engineering design based problem: identification of the problem parameters, such as useful information given, and unknowns. Metacognition is involved in mental activities such as identifying and selecting appropriate conceptual knowledge, planning a strategy to use the conceptual knowledge, monitoring one's progress towards a goal (Jonassen, 1997; White & Fredrickson, 1998). When the problem is encountered in a situation not within the confines of the classroom where the content was learned, the authentic problem demands the solver's ability to recognize the subject and specific content involved in the problem. Repeated experiences in solving such problems create the strong interconnected organization of information within a solver's long term memory and practiced habits of mind (Jonassen, 1997; Perkins & Salomon, 1989).

Based on various researchers' work on problem solving skills, the specific skills that can be associated with solving design problems that are not well-structured (not quite ill-structured, but authentic as previously described) can be identified as – 1) recognizing and identifying the problem, 2) recalling and organizing specific subject content relevant to the problem, 3) carrying out the procedural steps that are common practices within the subject, 4) looking back to see if the progression is logical, and, 5) stating the solution to the identified problem (Newell & Simon, 1972; Polya, 1973; Perkins & Salomon, 1989; Heller & Reif, 1984; Reeff, 1999). To develop a method of assessment would require specific ways to measure students' acquisition of these skills.

Review of Previous Techniques of Student Assessments on Problem-solving

A review of published research between 2000 and 2015, using the keywords "student achievement", "engineering", "STEM education", "problem-solving" and "design-based", and specifically targeting student participants from secondary and postsecondary programs, provided an initial count of 82 papers. Upon reviewing the abstracts, several papers were rejected from further review because they were either too narrowly focused within a specific discipline of STEM, or were too broadly focused on overall program assessment and thus, did not fit into the purpose of this review. As shown in Table 1, only six studies explicitly focused their investigations on students' problem solving skills.

Table 1

Summary of types of programs and measures of student achievement previously researched

Type of Student Achievement Measured	Self-Efficacy	Design Skills	Problem Solving	Spatial Analysis	GPA	Math-Sci Scores	Retention in STEM	Persistence in program	Interest Development	**Total**
Type of Program										
K-12			1		1				3	5
4-year college	2	3	5	1					1	12
Summer camp or short experience						1				1
Total # of studies by type	**2**	**3**	**6**	**1**	**1**	**1**	**0**	**0**	**4**	**18**

Of the six studies, only one was using high-school students as their participants, which suggests a void in the research on problem solving skills among students in secondary education. For purposes of this study however, among these six, there were four research studies that focused on problem-solving skills and were relevant (see Table 2) for methods used to assess students' problem-solving skills.

Eseryel, Ifenthaler and Ge (2013) focused on evaluating 9th grade students' ill-structured and complex problem solving skills using an experimental automated reasoning tool. The study tested and validated the developed tool using an adapted protocol analysis method (APAM). The researchers found that the automated tool and the APAM did not measure problem solving on an identical conceptual level. Steif, Lobue, and Kara (2010) examined problem solving and promotion of thinking about conceptual knowledge in the subject of engineering mechanics (Statics). The conclusions of this study were that when instructional strategies emphasize metacognitive processes to seek and describe useful information in the initial stages of solving a problem, students are generally more successful in solving the problem.
Describing and generating explanations are indicators of deeper understanding of content and successful problem solving. Taraban, Craig, and Anderson (2011) also focused on engineering mechanics, and designed their study to identify solvers' skill levels using specific indicators in their paper and pencil solutions.

Table 2.

Relevant research studies focused on measuring students' problem solving skills

Previous research	**Type of program**	**Specific usefulness for assessing problem solving skills.**
Docktor & Heller, 2009	Physics for science & engineering - 1st year students	Strong rubric developed. Construct validity established. Reliability across different problems also established. Context of problem: physics domain.
Eseryel, Ifenthaler & Ge, 2013	9th grade students	The automated tool developed, and the protocol analysis method used did not measure problem solving on an identical conceptual level.
Steif , Lobue & Kara, 2010	2nd or 3rd year engineering students	Concluded that describing and generating explanations are indicators of deeper understanding of content and successful problem solving.
Taraban, Craig & Anderson, 2011	2nd or 3rd year engineering students	Reliable evidence for PS ability indicators were found in the paper & pencil solutions. Use of metacognitive prompts were important to elicit student responses to show CT.

The specific indicators hypothesized were, 1) symbolic representation and diagram to describe the context of the problem, 2) specification of assumptions and principles applicable, 3) devising a strategy and executing the plan, and, 4) checking equations and solutions. Using a video recording of students thinking aloud with prompts, and students' paper and pencil solutions, the researchers confirmed that reliable evidence for problem solving ability indicators were found in the paper & pencil solutions when supported by using data from the video recordings. The use of prompts was important to elicit student responses on specific thinking about why certain decisions were being made in the process of solving the problem.

These studies confirmed that students' thinking processes and skills in problem solving can be revealed when appropriate question prompts are asked. The significance of this contribution for this study is best presented with an example. When working on rewriting a formula to solve for a variable, a solver will often skip steps because of familiarity with that technique. As a result, when substituting numerical values in the formula there is a strong potential that the solver could make an arithmetic error and get an incorrect answer. Therefore, when confronted with an incorrect answer and without seeing all the steps that were used in rearranging the formula and substituting the values, the solver is not able to ascertain whether the error was simply arithmetic or a deeper problem based on not knowing how to correctly rearrange a formula to solve for the unknown. Instructionally it is therefore necessary to require all the steps to be shown in order to diagnose the mistake and identify the skill that needs remediation. For purposes of this study, in order to reveal CT and PS while students solve a design challenge, specific questions prompts were used to elicit responses that are directly related to the identified skills in problem solving stated in the research sub-questions.

The study conducted by Docktor and Heller (2009) was designed to develop and test an easy to use physics-specific problem-solving assessment rubric for paper-and-pencil solutions when used with context-rich (or authentic) problems. The rubric was determined to be reliable, valid and useful to assess authentic problem solving skills in the physics domain. Key categories of assessment were identified for successful problem solving measures within the context of a physics based problem. These categories are - 1) useful description (symbolic and descriptive), 2) selection of physics content and use in solving the problem, 3) selection of mathematical content and use in solving the problem, and, 4) logical progression towards a solution. As previously discussed, these categories can be mapped onto the problem-solving process identified by several researchers (Newell & Simon, 1972; Polya, 1973; Perkins & Salomon, 1989; Heller, 1992; Reeff, 1999).

A review of three years (2013 to 2015) of published articles in Journal of Engineering Education (JEE) and the International Journal of Engineering Education (IJEE), revealed sparse research conducted with K-12 students as the primary participants. This review, and other research reports (NRC, 2010) confirm the need to focus on K-12 student achievement in CT and PS to better understand the benefits, and the potential for integrative STEM education. When K-12 students were participants in the research, the data collected were mostly related to either short summer camps where students were exposed to some specific instructional strategy, or the focus was regarding interest development among students through motivation based or self-efficacy based techniques. The glaring shortcoming is that none of the researchers focused on student achievement using acquired skills over a multi-year instructional program using the I-STEM ED pedagogical approach.

Implications for Designing Research to Assess CT and PS in K-12 Engineering Classes

Three studies from the review described earlier have strong influence on a potential research design to assess CT and PS in K-12 engineering classes and in a multi-year I-STEM ED instructional program. They are those studies conducted by Docktor & Heller (2009), Steif, Lobue, Kara & Fay (2010), and, Taraban, Craig, & Anderson, (2011). In these three studies, the common theme was assessment of student problem-solving skills in the discipline of physics or the sub-discipline of mechanics (Statics). The participants in the 2009 study were first year science and engineering students registered for the introductory calculus based mechanics course. The 2010 and 2011 studies were situated within the context of engineering students engaged in the first course in engineering mechanics: Statics. Methodological details, specifically the design of an instrument used to collect data, the researchers' assessment of the extent to which their study was successful in achieving the goals stated, and the relevance of the research to the current focus, of the three above-mentioned studies are discussed in the next sections.

Development of a PS rubric

The research conducted by Docktor & Heller (2009), was aimed at developing, testing and validating an easy-to-use problem solving rubric to assess students' problem solving skills in the physics domain. Specifically, their intent was to develop an easy to use method to assess the quality of the procedures and reasoning, in addition to the more commonly assessed correctness of end-results. The problem tasks used in the 2009 study were characterized as authentic and context-rich. Context-rich problems are short stories where the statement is not explicit about what variable is unknown, the problem may present more information than necessary or some information may be assumed as known to all, and solvers would need to make some reasonable assumptions prior to solving the problem (Heller and Keith, 1992). These types of problems may have one or more of the above mentioned features in common with real-world problems and may be also be called authentic problems (ibid). The 2009 study was also intended to make sure that this rubric was "applicable to any problem solving format used by a student, and to a range of problem types and topics typically used by instructors" (Docktor, 2009, p. 1).

The research conducted by Docktor and Heller (2009) is important because of the rubric that was developed to score any type of physics-based authentic problem. The rubric has five main categories that relate to established definitions of problem-solving and critical thinking (Newell & Simon, 1972). Established for this rubric was validity for generalizability across different populations and contexts, including those similar to traditional text book problems as well as those that are context-rich. The five broad categories (using a Likert scale from zero to five for assigning point values) addressed by this rubric are organizing problem information into a useful description, selecting and applying appropriate physics principles, selecting and using mathematical procedures appropriately, and the overall communication of an organized reasoning pattern (Docktor & Heller, 2009).

Use of Metacognitive Prompts

As previously discussed, conceptual knowledge is not sufficient for solving authentic problems, recognizing the relevant content in the context of the problem, and knowing when and how to apply the relevant knowledge. Metacognitive strategies of identifying useful information and the approach to solving the problem are thinking processes that need to be explicitly demonstrated in order to assess solvers' PS and CT skills. The two studies conducted by Steif, et al. (2010) and Taraban, et al. (2011), demonstrated the use of metacognitive prompts to elicit deeper thinking and explanations of specific PS skills. Using sketching (also known as free body diagrams in physics and mechanics) and descriptive language to explain understanding of the problem given both are important to successful problem-solving, and as indicators of solvers' ability to select and apply appropriate conceptual knowledge in physics (Steif, et al., 2010). Reliable evidence of solvers' problem-solving skills can be found in paper-and-pencil solutions when appropriate metacognitive prompts for the specific PS skills indicators are provided to solvers' in order to elicit explanations of their thinking (Taraban, Craig, & Anderson, 2011).

Potential for Assessing Key Student Abilities with a Scoring Rubric

To assess the five key student abilities contributing to CT and PS, a modified version of a rubric previously developed by Docktor & Heller (2009) to "provide a minimal measure that can be used to assess problem-solving independent of instruction or type of problems used" (p. 1) can be used.

Modification of the Rubric

The 2009 rubric developed by Docktor & Heller had five categories as described below:

1) Useful Description - refers to the process of summarizing information from a problem statement in an appropriate and useful form, such as assigning mathematically useful symbols to quantities and visualizing the situation with a sketch.
2) Physics Approach - is the demonstration of knowledge of physics concepts and principles associated with the problem and showing an understanding of those concepts.
3) Specific Application of Physics - is the process of selecting and linking appropriate physics concepts and principles to the specifics of the problem.
4) Mathematical Procedures - are the mathematical operations used to obtain the desired physics quantity.
5) Logical Progression - is the extent to which the solution is focused and consistent.

For purposes of developing a modified rubric, “useful description” can be separated into two parts – the descriptive aspect of the category was separate from the graphical representation of the useful description. Researchers have identified both these skills as essential components of problem identification, and therefore, separating the two skills into separate prompts would ensure that all students respond to both those skills (Heywood, 2005; Jonassen, 1997; Jonassn, Stroebel & Lee, 2006). Furthermore, the second and third items (Physics Approach and Specific Application of Physics) could potentially be combined in the selection and utilization of the science content and practices.

It would be necessary to align and validate the modified rubric through a study using I-STEM ED experts. Through an iterative process of consensus building among the experts, the modified rubric can be finalized. For conducting a study, using a sample of students from an I-STEM ED program and administering a design-based assessment, researchers have shown that when using rubrics, inter-rater reliability can be achieved through training and having no more than two raters (Jonsson & Svingby, 2007; Moskal & Leydens, 2000).

Conclusions

In an integrative STEM education program, all five of the 21st century skills (Creativity, Collaboration, Communication, Critical Thinking and Problem Solving, Citizenship) are learned and practiced within the context of the T/E DBL pedagogical approach. From a perspective of learning theories, the T/E DBL approach provides the context for student engagement (and motivation) through a design challenge. The design and testing of a solution involves an iterative approach to student learning and utilizing content and practices of the STEM disciplines. Specifically, CT and PS are involved in predicting, designing, testing and re-iterating, which are not practiced in traditional classrooms. CT and PS skills are also not assessed in traditional science and mathematics standardized testing. When students are tested for their problem solving abilities in the traditional classroom the focus is on the extent of correctness of the end-result, and rarely, if ever, on the reasoning or procedures leading to the result (Docktor & Heller, 2009; Shavelson, Ruiz-Primo, Li & Ayala, 2003; Steif & Dantzler, 2005). Furthermore, the content knowledge tested is directly related to what has been recently taught in the classroom, which does not require the solver’s demonstration of metacognitive processes involved in CT that require selecting the discipline specific content knowledge.

Research into the nature and characterization of problem solving over several decades has identified a set of student abilities requisite of success for solving authentic problems outside the confines of a typical classroom (Newell & Simon, 1972; Polya, 1980; Perkins & Salomon, 1989;

Martinez, 1998; Jonassen, Stroebell & Lee, 2006). Specifically, these student abilities are: 1) Useful description, both symbolic and descriptive, 2) Recognition and selection relevant science and mathematical content applicable to the problem, 3) Use of the principles and practices of specific content identified to solve the problem, and 4) adherence to a devised logical strategy for solving the problem.

Implications

The need for further research within technology education has been well documented by several researchers (Zuga, 1995, 2000; Cajas, 2000; Kolodner, 2000). Specifically research on how students select and utilize science principles previously learned in solving T/E design-based problems, using a qualitative approach would provide additional insights into student learning and transfer of their learning. The development of authentic design challenges and assessment instruments are needed for demonstrating the benefits of the integrative STEM ED pedagogical approach in developing CT and PS skills among students. In traditional Tech-ED classrooms, assessments lack specific focus on the CT and PS skills. The development of an assessment and rubric will provide opportunities to introduce these skills in the classroom and further, provide opportunities for further research on the benefits of I-STEM ED pedagogical practices. Furthermore, the availability of assessment instruments for CT and PS will create opportunities for more widespread use of the T/E DBL approach in science and math classrooms and provide a way for demonstrating student achievement.

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