

Investigation of Problem Solving Skills among 12th Grade Engineering Students

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ABSTRACT

(Academic)

US competitiveness in the 21st century global economy depends on a workforce that is science, technology, engineering and mathematics (STEM) literate, and has knowledge and skills to tackle complex technological problems. In response to the need for a STEM literate workforce equipped with 21st century skills there is a push for K-12 educational reform. STEM literacy is the ability to use content knowledge and skills in science, technology, engineering and math in solving human problems in a collaborative manner (NRC, 2009, Wiggins and McTighe, 2005). 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, with active construction of understanding by doing (Cajas, 2001; Wells, 2010, 2016b)

Critical thinking and problem solving (CT and PS) skills, collectively identified as 21st century skills by P21 (2005a), involved in solving authentic design problems are not assessed in traditional science and mathematics standardized testing or in Tech-ED classrooms in K-12 grades. Assessments in traditional classrooms, focus 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, and eliminates the need for solvers' demonstration of metacognitive processes involved in CT and PS that require recalling/selecting the discipline specific content knowledge. Within traditional Tech-ED classrooms, students are assessed using competencies defined in the Career and Technical Education curriculum framework which do not focus on solving authentic problems. Herein lies the gap between what is needed for the 21st century worker and what is currently the focus of secondary education.

The purpose of this study was to measure the extent to which students immersed in an I-STEM ED program were successful in solving an authentic design-based problem presented to them outside the context of the classroom where the content was learned. In addition, five specific student abilities (SAs) that contribute to authentic problem-solving were identified and a rubric to assess these SAs was developed and validated. A design-no-make challenge (DNMC) was developed and administered to these students.

Analysis of their responses showed that students immersed in an integrative STEM education program performed significantly better in designing a solution to the DNMC when compared with students in a traditional classroom. Furthermore, the specific SAs associated with selecting and utilizing the relevant science and math content and practices, and communicating logical reasoning in their design of a solution were found to be strongly correlated to students' successful problem-solving.

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ABSTRACT

(General)

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. In response to the need for a STEM literate workforce equipped with 21st century skills there is a push for K-12 educational reform, with an emphasis on the use of content knowledge and skills in science, technology, engineering and math in solving authentic problems in a collaborative manner. Collectively identified as one of the 21st century skills, critical thinking and problem solving skills involved in solving authentic design problems are not assessed in traditional science and mathematics standardized testing or in most technology education K-12 classrooms. Furthermore, the content knowledge tested is directly related to what has been recently taught in the classroom. Solvers therefore are not required to demonstrate recalling/selecting the discipline specific content knowledge which are part of critical thinking and problem solving.

The purpose of this study was to measure the extent to which students immersed in an I-STEM ED program were successful in demonstrating their critical thinking and problem solving skills by solving an authentic design-based problem presented to them outside the context of the classroom where the content was learned. In addition, five specific student abilities that contribute to authentic problem-solving were identified and a rubric to assess these SAs was developed and validated. To assess and measure the success, a design (no-make) challenge was developed and aligned with the rubric to assess these student abilities.

The results of the study indicated that students immersed in an integrative STEM education program performed significantly better in designing a solution to an authentic problem when compared with students with similar math and science coursework in a traditional classroom. Furthermore, of the five student abilities identified, three abilities related to selecting and utilizing the relevant science and math content and practices, and communicating logical reasoning in their design of a solution were found to be strongly correlated to students' successful problem-solving.

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As I write this last piece of my dissertation, it occurs to me that anything I say here may seem to be an afterthought. However, none of these thoughts are afterthoughts.

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List of Acronyms

AP – Advanced Placement

ASVAB – Armed Services Vocational Aptitude Battery

BLS – Bureau of Labor Statistics

CTE – Career and Technical Education

CT – Critical Thinking

DNMC – Design-no-make-challenge

ITEEA – International Technology and Engineering Educators Association

IRB – Institutional Research Board

NAE – National Academy of Engineering

NAGB – National Assessment Governing Board

NRC – National Research Council

NCES – National Center for Education Statistics

OSS – Overall Success Score

PBL – Problem Based Learning

PjBL – Project Based Learning

PPM – Pearson Product Moment

PS – Problem Solving

RQ – Research Question

SA – Student Abilities

STEM – Science, Technology, Engineering and Mathematics

T/E DBL – Technology/Engineering Design Based Learning

CHAPTER ONE: INTRODUCTION

21st Century workforce needs

The need for science, technology, engineering and mathematics (STEM) literate citizens in the 21st century is well documented (ITEA/ITEEA, 2000/2002/2007, NAE and NRC 2002, NGSS, 2013). U.S. competitiveness in the global economy depends on the development of a workforce with knowledge and skills to tackle complex technological problems (Katehi, Pearson & Feder, 2009). In this changing, fast-paced, global economy, graduates need to know how to make complex arguments and solve problems they have never seen before (Ripley, 2013, Friedman, 2005). The Bureau of Labor Statistics (BLS) projects that the science and engineering workforce will have 1.1 million new jobs in this decade, and, 1.3 million scientists and engineers will be needed to replace the ones who exit the workforce (2013).

In response to the need for a STEM literate workforce equipped with 21st century skills, there is a push for K-12 educational reform to prepare students adequately to fill the need. 21st century skills have been identified as critical thinking and problem solving, communication, creativity, collaboration and (recently added) citizenship (P21, 2015a). STEM literacy is the ability to use content knowledge and skills in science, technology, engineering and math in solving human problems in a collaborative manner (NRC, 2009, Wiggins and McTighe, 2005). The development of standards for technological literacy (ITEA/ITEEA, 2000/2002/2007), the inclusion of engineering in science education (National Science Board, 2007), and the call for interconnectedness of the disciplines in STEM education are all efforts to reform education to meet the 21st century needs (NRC, 2009).

The problem

In contrast to the 21st century needs mentioned above and the efforts at educational reform, US students continue to perform close to the bottom of the list in international assessments when compared with thirty industrialized countries in the world (NCES, 2012; Pope, Brown, & Miles, 2015). Data from the Trends in International Mathematics and Science Study (TIMSS) and Program for International Student Assessment (PISA) show that US students continue to lag behind in mathematics and science literacy (NCES, 2012). The PISA, designed to measure literacy in these subject areas rather than curriculum based content knowledge, targets students' abilities in utilizing their knowledge in these subject areas for problem solving in other contexts (NCES, 2012; Pope et al., 2015). These measures are at least as relevant, if not more relevant than other in-school standardized testing which only require students to access their subject content and procedural knowledge to solve problems in the school setting. The PISA results from 2012 indicate that the US ranks 34th in mathematics literacy and 28th in science literacy in the world (NCES, 2012). Furthermore, no improvement has been noted over the years, as these scores were not any different than the scores of US students testing in the PISA in 2003, 2006, and 2009 (NCES, 2012).

The TIMSS results from 2011 (NCES, 2012) show that students from seven countries scored better than the US students in both science and math. The TIMSS assessments provide data on student achievement in math and science in grades four and eight. Another example of US students' performance in testing outside schools is the army entrance exam. According to The Educational Trust (2010), 23 percent of students testing for the army entrance exam (Armed Services Vocational Aptitude Battery, ASVAB) fail this foundational exam. These results show that US educational reforms and the various standards developed and implemented, have not

produced the results that were expected. Furthermore, students who have graduated high-school, and gained entrance to colleges/universities to pursue science and engineering studies are unprepared to use their high school math and science knowledge in their college coursework assignments that place demands on previously acquired foundational knowledge from their secondary education (Budney, LeBold & Bjedov, 1998; Steif & Dantzler, 2005). High rates of attrition result from this lack of preparation (Steif & Dantzler, 2005).

Rationale

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). This is the goal of Integrative STEM Education, which 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 and Ernst, 2012/2015)

Students taking all the required courses in science and mathematics for high school graduation, in many if not most instances, also pursue Advanced Placement (AP) credit in science, math, english, history and many more topics. Over-packed schedules for students and teachers are the realities of K-12 education (Pope, 2013). According to Pope (2013), these

students do not learn the content in a deep relevant manner, and instead are focused on scoring at least three points, the passing grade for any AP course to be accepted by colleges and universities. These students are less likely to pursue any other electives in high-school, as their intention is to pack their schedules with as many AP courses as possible (Pope, 2013).

In K-12 education, the implementation of an integrative STEM education approach is best suited to a technology education program (Wells, 2015). In Virginia, this includes a series of sequential courses with progressively more complex content from the existing curriculum framework outlined in Career and Technology Education (CTE) guidelines of the Department of Education (CTE, 2015). CTE courses are designed to provide an opportunity for teachers to engage students in designing solutions to complex problems through research and discovery. However, these courses are not required for graduation, fall under the category of electives, and thus, compete with AP coursework that students find more desirable. While AP courses are considered desirable from the perspective of college admissions, AP courses have not been shown to benefit students in developing critical thinking and problem solving skills (Pope, 2013; Pope et al., 2015). The increase in the number of AP courses adds to students' stress that leads to rote memorization and a focus on passing the test with a minimum score to increase their attractiveness to colleges and universities (Pope et al., 2015). These effects are detrimental to students' learning.

Engineering (through its characteristic design-based pedagogical approach) offers a platform in K-12 education for integration of content and practices in the STEM fields, and provides opportunities for higher order learning because of higher cognitive demands in critical thinking and design-based problem solving experiences ((NAE and NRC, 2014; Katehi, Pearson & Feder, 2009; Sheppard, Colby, Macatangay and Sullivan, 2006; Wells, 2016a). In Virginia,

CTE offerings have a sequence of engineering coursework available that could be used as a framework for a 9-12 engineering program. Engineering by Design™ (EbD) is a flagship curriculum for ITEEA that uses sequenced CTE courses to provide a curriculum for 9-12 education. Another provider of P-12 engineering curricula, Project Lead the Way® (PLTW) includes both introductory and advanced course work in engineering. However, a major drawback is that these opportunities or programs do not exist in all schools due to the lack of funds, qualified teachers, or space, and, these programs are independent of the science and math coursework that the students take in their high-schools. Thus, all students do not get an opportunity to participate in such experiences, and even those who participate, do not get the opportunity for an integrative STEM education experience. Moreover, in many instances students do not choose to take these courses as their schedules are already burdened with their core requirements and various AP courses as mentioned before.

An alternative to the above programs is the more recent Virginia Department of Education's (VDOE) initiative of the Governor's STEM Academies (Academies) aimed at expanding the available "options for the general student population to acquire STEM literacy and other critical skills" (Governor's STEM Academies, 2016). The Academies are intentionally created to focus students towards investigations and learning at the intersections of the disciplines, and encourage students to explore the interrelated facets of the disciplines. The VDOE states that the Academies are designed to raise standards and use innovative content and methods to meet Virginia's STEM goals. These goals are:

- To maximize opportunities in preparing students for targeted careers, by breaking down barriers between traditional core academics and career and technical education (CTE);

between high school and postsecondary education and training; and between education and the workplace;

- To raise student aspirations and attract more students to postsecondary education in preparation for technical careers; and
- To provide well-trained workers to support the recruitment of new businesses and industries to the commonwealth and to meet the workforce needs of existing business and industry (Governor's STEM Academies, 2016).

The first goal recognizes that the traditional silo approach to teaching the core courses in high school separately from the CTE courses (that provide students the opportunity to experience the interrelatedness of the disciplines in practice) is a barrier to STEM literacy. In Virginia, twenty-three Governor's STEM academies exist as of 2016, where the designated programs meet one or more of the benchmarks established by VDOE. These benchmarks include providing the opportunity for students to earn at least nine college credits and demonstrate competency in postsecondary assessments such as the College-Level Examination Program (CLEP) or other placement tests. The Academies are designed with the flexibility of focus areas, courses (CTE and non-CTE courses) and practical experiences for all students (including internships, mentorships and projects). Based on the stated goals and outcomes for the Academies, such programs may help bridge the gap previously discussed, between what students actually learn through their high school curriculum, and the expected demonstration of STEM literacy outside the confines of the classroom. This initiative is also different from the older Governor's schools initiatives which focus on math and science curriculum without significant emphasis on the practice of the STEM disciplines in the workplace. VDOE states that the Academies are a

“practical complement” to the previously introduced Governor’s schools (Governor’s STEM Academies, 2016).

On the surface, it appears that these Academies may have the potential, through the innovative approach to blending core courses (math and science), and design courses (CTE based courses) to create the opportunity for students to be engaged in the integrative STEM pedagogical approach at the “natural intersections of learning within the continuum of content areas” (Wells and Ernst, 2012/2015). As Wells (2008) explains “integrative STEM education fosters a blended pedagogical approach and establishes the curricular foundations that have long been supported by cognitive research” (p. 11). This study was intended to address 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 (Cajas, 2000; Kolodner, 2000; Zuga, 2000).

Purpose of the Study

The purpose of this exploratory, descriptive research study is to add to the research base regarding the use of the T/E DBL pedagogical approach within an integrative STEM education program as an instructional strategy for enhancing students’ critical thinking and problem solving skills they evidence through their utilization of acquired science and math concepts in problem solving experiences situated outside the confines of those particular classes. In a Governor’s STEM Academy (Academy) engineering program, students have the opportunity to take progressively complex engineering courses every year along with science (physics and chemistry) and math courses that are well integrated in the overall curriculum. To document critical thinking (CT) and problem solving (PS) skills of senior students immersed in such an

integrative STEM educational experience, data were collected to assess the demonstration of specific student abilities in the problem solving process. The analysis of the collected data was used to document the CT and PS skills of the students.

Research Questions

The following research questions (RQs) were used to guide this study:

1. In the context of an engineering program within a Governor’s STEM Academy (Academy) employing the integrative STEM ED pedagogy, to what extent are students successful (Overall Student Success – OSS) in using engineering, science and mathematics for solving an authentic design-based problem outside the confines of the classroom where the subjects were originally taught?
2. How are the key student abilities in CT and PS correlated to overall student success (OSS)? Specifically what is the strength of the relationship of the following key student abilities (SA) with their success (OSS) in solving the authentic design-based problem:
 - a) Ability to organize essential information from a design challenge into appropriate and useful representations descriptively to guide the process of designing a solution.
 - b) Ability to organize essential information from a design challenge into appropriate and useful representations graphically to guide the process of designing a solution.
 - c) Ability to select and use relevant science content and practices necessary in the design of a solution.
 - d) Ability to select and use relevant mathematics content and practices necessary in the design of a solution.

e) Ability to demonstrate logical progression towards a solution.

Limitations

1. This study was limited to the context of a particular Governor’s STEM Academy Engineering program.
2. This study was limited to authentic problem-solving skills assessment and not of ill-structured problem solving skills of students as encountered in the practice of engineering.
3. The study was comprised of a small sample (fewer than twenty) and results cannot be generalized to other populations. As an exploratory study, it was not intended to provide comparisons or results that can be used for predictions or generalizations.

Definitions

Cognitive demands

Cognitive demands are the four hierarchical levels within the cognitive domain and include declarative, procedural, schematic, and strategic knowledge (Shavelson, Ruiz-Primo and Wiley, 2005; Wells, 2016a).

Declarative knowledge type

Declarative knowledge includes the knowledge of facts and concepts, and reflects an individual’s knowledge of “that” (NAGB, 2009; Shavelson et al., 2005).

Design

“An iterative decision-making process that produces plans by which resources are converted into products or systems that meet human needs and wants or solve problems” (ITEA/ITEEA, 2000/2002/2007, p. 237).

Integrative STEM education

“The application of technological/engineering design based pedagogical 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).

Procedural knowledge type

Procedural knowledge or knowing “how” reflects an individual’s knowledge of processes (NAGB, 2009; Shavelson et al., 2005).

Schematic knowledge type

Schematic knowledge consists of knowing “why” or the reasoning and relationships between concepts (NAGB, 2009; Shavelson et al., 2005).

Strategic knowledge type

A person’s understanding of “when, where and how” to apply their knowledge is considered strategic (NAGB, 2009; Shavelson et al., 2005).

Technological literacy

“The ability to use, manage, assess, and understand technology” (ITEA/ITEEA, 2000, 2002, 2007, p.9).

Technological/Engineering design process

“A systematic problem-solving strategy, with criteria and constraints, used to develop many possible solutions to solve a problem or satisfy human needs and wants and to 11 winnow (narrow) down the possible solutions to one final choice” (ITEA/ITEEA, 2000/2002/2007, p. 237).

CHAPTER TWO: LITERATURE REVIEW

Theoretical Premise

The shortfall in the intended outcomes for students' achievement of the implied higher order thinking skills, characterized by the one of the five C's of the 21st century skills – Critical thinking and problem solving (P21, 2015a), is the focus of STEM education reform. Specifically, outside of the confines of the 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). Critical thinking and problem solving skills are associated with schematic and strategic knowledge types (Webb, 1997; Gagne, et al., 2004).

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. Technology education (Tech-ED) framework has traditionally been geared for student learning through the content and practices of technological and engineering design. However, not all students are able to access the 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).

To further identify and characterize the nature of the problem and areas of research critical to this study, a review of relevant literature was conducted. This chapter focuses on four areas that are significant in the development of this research study. The first section explores the foundations of STEM education, and theories of learning that underpin integrative STEM education (I-STEM ED) and the pedagogical approach of I-STEM ED. The second section focuses on the need for critical thinking (CT) and problem solving (PS) skills development to

meet the 21st century educational goals, and the relationship of CT and PS skills to the T/E DBL approach used in I- STEM ED. The third section summarizes research on assessing student achievement through the lens of CT and PS, and gaps in the research. Finally, the motivation for this research design, data collection methods and the instrument used in this study are discussed.

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 and 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 “siloeed” (NAE and 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 and 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 and 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 the STEM education in K - 12 grades. Engineering education in K-12 has no separate standards due to overburdened curricula in secondary education, and lack teacher preparedness for teaching 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 a mental process of 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, and 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, 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 and Cocking, 2000; Brown, Collins and Duguid, 1989). Furthermore, learners' construction of knowledge is linked to the activity, context and culture in which it is learned (Brown, Collins and Duguid, 1989).

Although learning occurs in a collaborative or social context, this 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 and 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 novel situations, active construction of understanding by doing (Wells, 2016b, p. 15). Within 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 and 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 the recognition of the need for integration, focus 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 et al., 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 contents 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 and 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, 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, but as previously noted, these courses are 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 and McTighe, 2005; Felder

and Brent, 2016). Based on the researcher's experience, the interpretation of hands-on learning for instructional purposes has been with a focus on project-based learning (PjBL). More often, in technology education classrooms, a PjBL approach is used. Students are provided an end-goal for a project, instruction on how to accomplish the end-goal, detailed instruction on the hands-on aspects, and assessment is directly tied to the various parts (what one can see, hear, and touch) of the project. As Felder and Brent (2016) also note, this approach is teacher-centered and does not imply that 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 (Felder and Brent, 2016, p. 6).

One method is to engage students in learning experiences that are inquiry based, are embedded in a challenge that is relevant to their lives, and requires them 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 and 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 (John 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 students. 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 problems in life 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, supported by research on how people 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 and 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. The PIRPOSAL© model for this T/E DBL approach “embraces” (Wells, 2016b, p. 15) the integration of the STEM disciplines. 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 in Virginia. 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 for 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 in the CTE course, where disciplinary content in science and math are not the focus of instruction. 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, a last poorly defined skill is managing real-world problems (CTE, 2015), which is further explained as researching the context of a local problem and interviewing professionals on the various aspects of the problem. 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 PjBL, but not 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 can have high scores in their science and math assessments, and have achieved a high level of competency in skills measured by CTE standards, but because the two assessments are neither related nor are they conducted in the same context, students do not practice or demonstrate their critical thinking and problem solving skills. Therein lies the gap between what is needed for a 21st century worker, and what is currently being focused on in secondary education. This relates directly to the reason for the poor performance in assessments that are not within the confines of the classroom, such as the PISA and the TIMMS previously discussed.

In the report on Discipline Based Education Research (DBER) (NRC, 2012a), the committee, the board on science education and the division of behavioral and social sciences and education, summarized their recommendations regarding future directions of DBER to include more studies on the K-12 students' transition to college in order to better understand the acquisition of important interdisciplinary cross-cutting concepts in STEM using better measures of outcomes (other than test scores and course performance) in order to influence retention and persistence of student 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 and 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, are 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 students to be caused to learn and practice all these skills. Furthermore, including engineering design within science and mathematics instruction only introduces students to the design process without experiencing the integrative and interdisciplinary approach embedded in I-STEM ED. The focus of this study was to assess students' abilities that demonstrated CT and PS skills, when immersed in an integrative STEM education pedagogical approach through their high school years. These student abilities were assessed using an authentic design-no-make challenge (Barlex, 2003), which is similar to the format of the questions in the PISA, where students are required to use their mathematics and science content knowledge in solving problems set in real-world contexts.

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 multiple disciplinary experts, 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 problem situated in the context of science and mathematics, and requiring the design of a solution (such as in a design-no-make challenge), the method may be heuristic in the creating general strategies for solving the problem, but algorithmic when it comes to utilizing specific mathematics and science knowledge to solve the problem. In addition, frequently practiced and accessed pathways to stored content in long-term memory helps 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 help with progressing 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 and 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, Stroebe and Lee, 2006; Chi, Feltovich, and Glaser, 1981). 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; Chi, Feltovich, and Glaser, 1981; White and Fredrickson, 1998). When the problem is encountered in a situation not related to 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 and Simon, 1972; Polya, 1973; Perkins & Salomon, 1989; Heller & Reif, 1984; Reeff, 1999). The ways in which research on assessment of problem-solving skills has been conducted in the past helped direct an appropriate method for this study.

Techniques of student assessments on problem-solving

The purpose of this review was twofold:

- 1) To identify the ways in which students' achievement in K-12 engineering or STEM programs have been investigated or assessed;
- 2) To identify the relationship of those investigations or assessments techniques to CT and PS.

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. The complete detailed results of the review, method used for evaluation of the research articles, and the data tables generated by the review are included in *Appendix H*. 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

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 who's focus on problem-solving skills was relevant (see Table 2) for methods used to assess students' problem-solving skills.

Eseryel, Ifenthaler & 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.

Table 2

Relevant research studies focused on measuring students' problem solving skills

<u>Previous research</u>	<u>Type of program</u>	<u>Specific usefulness for assessing problem solving skills.</u>
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 and 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.

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. 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 will be 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 and Simon, 1972; Polya, 1973; Perkins and Salomon, 1989; Heller, 1992; Reeff, 1999).

A review of three years 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 Research Design

Three studies from the review described earlier have strong influence on the method employed in the conduct of this study. They are those studies conducted by Docktor and Heller (2009), Steif, Lobue, Kara and Fay (2010), and, Taraban, Craig, and 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 study, of the three above-mentioned studies are discussed as they relate to development of the research method employed in this study.

Development of a PS rubric for this study

The research conducted by Docktor and 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 in this research 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 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). The rubric uses a likert scale from zero to five for assigning point values. The 2009 rubric was adapted for use in this study and is described more fully in Chapter three.

The 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). Based on this 2011 study questions designed to be metacognitive prompts were developed to cue

students to specifically align with both ability indicators in the adapted rubric and the research questions in this study.

Literature Summary: Research Design to Assess CT and PS

The literature review resulted in identifying relevant research studies on students' PS skills in physics and its sub-discipline of mechanics, which contributed to the development of the instruments and the data collection in this study. 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. CT and PS skills are 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.

For the problem solving activity in this study, a design-based problem was chosen. Design-no-make (DNM) was introduced by David Barlex in 1999 through the Young Foresight initiative (Barlex, 2003). At the time it was introduced, it was aimed at helping focus students' learning, and teachers' instruction towards the design phase instead of making the designed product. Research showed that this approach is valuable in helping students explore a wide range of design criteria, helps develop more understanding of the technological concepts, and that students enjoyed the experience as well (Barlex & Trebell, 2008). From an instructional perspective, the distractions of making the prototype were removed from the learning experience,

and thus gave students the opportunity to explore various ideas and concepts in greater depth (Barlex & Trebell, 2008). In the current study, this type of a DNM challenge was equally suitable and instrumental in revealing students' use of schematic and strategic knowledge domains (previously described) correlated to CT and PS skills.

For purposes of this study, the authentic context of the design-based problem used was situated in the physics and mathematics content areas. Both physics and mathematics were components of the curriculum in the Academy. Researchers have found that lack of literacy in these two content areas (physics and mathematics) as contributing to the challenges faced by undergraduate students in engineering programs (Budney, LeBold & Bjedov, 1998; Steif & Dantzer, 2005). One of the reasons students drop out or transfer out of engineering programs is that they are inadequately prepared to apply the foundational knowledge in these subjects (ibid).

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 of relevant 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. This research study used parts of the previously discussed studies to develop, validate and utilize an assessment rubric to answer the research questions and sub-questions stated. The research methodology and procedures, along with instrument development, phases of the study, and data collection procedures, are described in the following chapter.

CHAPTER THREE: RESEARCH METHOD

This chapter describes the method used to research the questions posed in this study. The following sections describe the research design, study participants, instruments, data collection procedures used, and the resulting summary. To answer the research questions guiding this study, the investigation employed an exploratory case study research design to collect and convert qualitative data to quantitative data through the use of a scoring rubric. In the context of an engineering program within a Governor’s STEM Academy (Academy) employing the integrative STEM ED pedagogy, the research questions (RQs) guiding this study are:

1. To what extent are students successful (Overall Student Success – OSS) in using engineering, science and mathematics for solving an authentic design-based problem outside the confines of the classroom where the subjects were originally taught?
2. How are the key student abilities in CT and PS correlated to overall student success (OSS)? Specifically what is the strength of the relationship of the following key student abilities (SA) with their success (OSS) in solving the authentic design-based problem:
 - a) Ability to organize essential information from a design challenge into appropriate and useful representations descriptively (SA1) to guide the process of designing a solution.
 - b) Ability to organize essential information from a design challenge into appropriate and useful representations graphically (SA2) to guide the process of designing a solution.
 - c) Ability to select and use relevant science content and practices (SA3) necessary in the design of a solution.

- d) Ability to select and use relevant mathematics content and practices (SA4) necessary in the design of a solution.
- e) Ability to demonstrate logical progression (SA5) towards a solution.

The following four phases of the study were developed using an exploratory sequential mixed-methods design (Creswell and Plano-Clark, 2011):

- a) Develop and align the design-based problem question prompts (metacognitive prompts) and the rubric used to score the student responses with the research questions for the study.
- b) Collect qualitative data by administering the design-based authentic problem with students from the Academy.
- c) Collect quantitative data using the scoring rubric previously developed.
- d) Conduct quantitative data analysis.

Research Design

This study examined student responses to a design-no-make challenge (DNMC) as a means for assessing their higher order thinking skills evidenced by their selection and utilization of science and math content to solve the problem described in the DNMC. The DNMC with prompts was developed using a physics-based authentic problem typical of the types of problems encountered by humanitarian workers of Virginia Tech, engineering students in their work in Malawi (<http://www.beyondboundaries.vt.edu/team-malawi.php>). In discussions with the co-founder, Dr. Andre Muelenaer, and physics educators in secondary education, the design challenge was first developed. Procedures for aligning the DNMC to the established curriculum standards for science and mathematics are described in the following sections. The metacognitive question prompts were developed in order to elicit responses to demonstrate key

student abilities (SAs) as identified in this study. The scoring rubric for the DNMC response was adapted from the rubric developed by Docktor (2009) to measure the key SAs identified as indicators of students' abilities to solve authentic problems outside the classroom where the related subjects were first learned. The adapted rubric is described in the following sections.

The dependent variables in this study were the overall student success (OSS) and the various Student Abilities (SA1, SA2, SA3, SA4 and SA5). To obtain measures for these SA, responses to the DNMC question prompts were scored using the adapted rubric, and thus providing a numerical score. The independent variable in this study was the I-STEM ED pedagogical approach used in the Academy over the four years of science, mathematics and engineering instruction (program coursework and sequence is provided in *Appendix A*).

The alignment between the research questions and the sub-questions, the data collection methods, and the methods of data analysis methods used are presented in Table 3. Qualitative data based on student responses were converted to quantitative measures using the adapted scoring rubric based on the one developed in 2009 by Docktor & Heller.

Table 3

Alignment between Research Questions, Sources of Data and Analysis.

Questions	Data Collection Method	Data Analysis
<p><u>Research Question 1</u> To what extent are students successful (Overall Student Success - OSS) in solving an authentic design-based problem outside the confines of the classroom where the subjects were originally taught?</p>	<p><u>Qualitative</u></p> <ul style="list-style-type: none"> • DNMC responses • Use of rubric to identify scores in the 5 categories <p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Sum of the scores obtained in all five SA categories 	<ul style="list-style-type: none"> • Descriptive statistics of rubric scores. • Shapiro-Wilk Test of normality of data • One-sample t-test/bootstrapping procedure

Table 3 Continued

Questions	Data Collection Method	Data Analysis
<p><u>Research Question 2</u> How are the key student abilities in CT and PS correlated to overall student success (OSS)? Specifically what is the strength of the relationship of the following key student abilities (SA) with their success (OSS) in solving the authentic design-based problem:</p>	N/A	N/A
<p><u>Sub-question 2a</u> SA1 - Ability to organize essential information from a design challenge into appropriate and useful representations descriptively to guide the process of designing a solution.</p>	<p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Rubric score for useful description 	<ul style="list-style-type: none"> • Correlation between OSS and SA1 • Adjusted rho – correlation coefficient
<p><u>Sub question 2b</u> SA2 - Ability to organize essential information from a design challenge into appropriate and useful representations graphically to guide the process of designing a solution.</p>	<p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Rubric score for sketch 	<ul style="list-style-type: none"> • Correlation between OSS and SA2 • Adjusted rho – correlation coefficient
<p><u>Sub question 2c</u> SA3 - Ability to select and use relevant science content and practices necessary in the design of a solution.</p>	<p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Rubric score for Application of Physics 	<ul style="list-style-type: none"> • Correlation between OSS and SA3. • Adjusted rho – correlation coefficient
<p><u>Sub question 2d</u> SA4 - Ability to select and use relevant mathematics content and practices necessary in the design of a solution.</p>	<p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Rubric score for Application of Mathematics 	<ul style="list-style-type: none"> • Correlation between OSS and SA4. • Adjusted rho – correlation coefficient
<p><u>Sub question 2e</u> SA5 - Ability to demonstrate logical progression towards a solution.</p>	<p><u>Quantitative</u></p> <ul style="list-style-type: none"> • Rubric score for logical progression 	<ul style="list-style-type: none"> • Correlation between OSS and SA5. • Adjusted rho – correlation coefficient

Analysis of data collected tested the significance of the average overall student performance score and explored the correlation between each of the SA and the OSS (Pedhazur and Schmelkin, 1991). The independent variable in this study was the integrative STEM ED design-based pedagogical approach used in the Academy, as described in Chapter Two. Development of the DNMC and adaptation of the rubric are described in the following subsections.

Instrumentation

Design-No-Make Challenge (DNMC)

The DNMC describes a scenario in a third-world country where there are limited resources and a need for accessing clean water. The description and the challenge provided to students is shown in Figure 1.

Figure 1. Design-No-Make Challenge

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and 1.0 hp = 746 W. For pricing, use the information provided in the attachment.

The following questions asked of the students were metacognitive prompts designed to reveal student thinking:

Q 1a) What is your understanding of the challenge described above? Describe using your own words, in a few sentences.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

For the last question, a price sheet was provided to the students, which included four options as shown in the Figure 2.

Figure 2. Submersible Pump Options and Pricing





			
\$48.30 / each	\$98.12 / each	Was \$79.05 \$71.13 / each Save \$7.92 (10%)	\$439.82 / each
ECO FLO 1/4 HP Submersible Utility Pump	ECO FLO 1/3 HP Submersible Utility Pump	Superior Pump 1/2 HP Submersible Thermoplastic Utility Pump	Koshin 1 in. 1 HP Centrifugal Pump with Honda Engine
Model SUP55	Model SUP56	Model 91570	Model SEI4-25L

Image obtained from the Home Depot printed catalogue from December 2016

Physics Standards addressed by the DNMC

Physics standards four and five of the Virginia Science Standards Curriculum Framework (2010) state:

PH.4: The student will investigate and understand how applications of physics affect the world. Key concepts include a) examples from the real world, and b) exploration of the roles and contributions of science and technology (p. 4).

PH.5: The student will investigate and understand the interrelationships among mass, distance, force, and time through mathematical and experimental processes. Key concepts include - g) work, power, and energy (p. 5).

Using Newton's Laws of Motion, students are required to demonstrate essential knowledge and skills by solving problems involving multiple forces, using free-body diagrams, and involving mechanical work, power, and energy (Virginia Science Standards Curriculum Framework, 2010, p. 5).

The DNMC was based in PH4 and PH5 standards and the context of the design challenge was associated with a real-world problem of designing a suitably sized (power) and priced (cost) submersible pump to help access underground drinking water for a less-developed (or third-world) community. The real world situation required resource consciousness (price) and the problem was authentic in that this problem was one of the many problems encountered by Virginia Tech engineering students (Team Malawi previously identified) during their humanitarian work. Furthermore, this problem involved using principles of power and work and the related formulas for power and work, in order to determine the suitable size or motor power of the submersible pump needed.

Mathematics standards addressed by the DNMC

The Mathematics Standards of Learning for Virginia Public Schools (VDOE, 2009), outlines the requirements for students' essential knowledge and skills in the "use of algebra as a tool for representing and solving a variety of practical problems" and "oral and written communication concerning the language of algebra, logic of procedures, and interpretation of results". Specifically, the following standards address what students should be able to do after completion of Algebra I and Algebra II, which are both exit requirements for high school graduation:

A.1: The student will represent verbal quantitative situations algebraically and evaluate these expressions for given replacement values of the variables

AII.10 The student will identify, create, and solve real-world problems involving inverse variation, joint variation, and a combination of direct and inverse variations.

The DNMC was designed to address these minimum standards and essential skills required for any student graduating high school.

Assessing Key Student Abilities with a Scoring Rubric

To assess the five key student abilities addressed in Research Question 2 (CT and PS correlation to OSS), 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) was used. This modified rubric was necessary in order to evaluate student responses to the DNMC.

Modification of the Rubric

The 2009 rubric developed by Docktor & Heller (henceforth referred to as the 2009 rubric) 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” was 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 as they relate to SA1 and SA2 in the research sub-questions (Heywood, 2005; Jonassen, 1997; Jonassn, Stroebel & Lee, 2006).

The second category of the 2009 rubric was related to a demonstration of understanding specific physics concepts and principles. Within this study, the purpose was clearly on the recall, recognition and utilization of specific physics concepts which are critical to being able to solve authentic problems (Perkins & Salomon, 1989). The demonstration of understanding of physics concepts and principles was not relevant, and was therefore eliminated in the adapted rubric. Research sub-question 2c focused on the ability to select and utilize the science content (SA3) in solving the design challenge, which aligns with the category of “Specific Application of

Physics”. Demonstration of the ability to use relevant mathematics content (SA4) is aligned with the fourth category of the 2009 rubric and therefore included in the modified rubric. The last category of the 2009 rubric aligns with sub-question 2e which focuses on students’ ability to demonstrate a logical progression towards a solution (SA5) and was therefore included in the adapted rubric.

The score levels in the 2009 rubric were from zero (worst) to five (best) in each category. An additional level of ‘NA’ (not applicable) was also eliminated from the modified rubric, because that level was envisioned for a universal rubric where some problems may not require a specific category or some solvers may demonstrate expertise where certain detail need not be shown (Docktor, 2009, p. 75). In this research study, the DNMC prompts explicitly require detailed responses and thus no response would earn a zero score. The modified rubric was then analyzed for alignment with the research questions and for validity and reliability by experts in I-STEM ED, as described in the next section.

Instrument Alignment and Validation

To ensure that the DNMC question prompts and the modified rubric aligned with the research questions in this study and could be reliably used for scoring student responses, a small group of I-STEM ED experts took part in a pilot study. Five students enrolled in a high school physics class were recruited and agreed to participate in providing responses to the DNMC which were scored by the experts. Individuals participating in the pilot study included the following:

1. Four experts (with doctoral degrees in I-STEM ED, and practicing in teacher education and professional development) in the field of I-STEM ED,
2. Five students enrolled in a high school physics class not in the Academy.

Approval from the Institutional Review Board (IRB) of the Board of Human Subjects at Virginia Tech, and a similar approval from the School District Research Review Committee was obtained prior to conducting the pilot study (refer to *Appendix B*).

The purpose of the pilot study was to finalize the method of data collection and the analysis of those data with the following goals:

1. Finalize the DNMC question prompts, as well as the scoring rubric, that was used in the study;
2. Align rubric categories with DNMC question prompts and RQ2 a-e.
3. Establish reliability of rubric for scoring student responses to the DNMC question prompts.

Each participating expert was given the description of the study (*Appendix C*) and the tasks involved in his/her role as expert reviewer. After they confirmed their agreement to continue with their roles, they were given a copy of the research questions, the purpose of the study and the DNMC with the question prompts (*Appendix D*). The experts were asked to review each of the question prompts (Table 4), and compare them to the associated research sub-question with the intent to rate the alignment of the question prompts to the research questions. Using a scale of one (poor) to four (excellent), the experts were asked to provide a numerical score for each question prompt and provide comments and suggestions for improvement of the prompts.

Table 4

First Draft of a Portion of the DNMCQ Provided to Experts

<p>Reviewers: <u>Please chose a number between 1 and 4 for your responses and then provide comments. 1 implies you disagree, 2 implies you somewhat disagree, 3 implies you somewhat agree, and 4 implies you agree.</u></p> <p>2) What physics formula(s) will you use in determining the power of the water pump? Explain your strategy in a few sentences.</p> <p><i>This question corresponds with Student Ability (SA) #2 as stated in the Student Abilities:</i></p> <p>SA2 - Ability to recognize science content and practices necessary in the design of a solution.</p> <p>Reviewer response: <i>Do you agree with the correspondence between the question asked and the SA#2 as stated above? Please choose a number between 1 and 4 based on your level of agreement. Enter your choice here: _____</i></p> <p><i>Please provide comments and/or suggestions below to help improve the question:</i></p>
--

Responses were collected, and based on the expert feedback needed adjustments were made prior to a second review by the panel in same manner. The intent was to obtain at least a score of 3 or above for all questions among the expert panel. Following two iterations, with corresponding revisions to the language of the question prompts, consensus was achieved (score of three or four) for all question prompts. A summary of the reviews is tabulated in Table 5. The finalized DNMC and question prompts are found in *Appendix G*.

Table 5

Summary of Expert Reviews with Final Version of Question Prompts

SA1 - Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.				
	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4
Round 1 scores	4	3	3	4
Round 2 scores	4	3	4	4

(Continued)

Table 5 Continued

Summary of expert reviews with final version of question prompts (continued)

SA2 - Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.				
	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4
Round 1 scores	4	2	3	4
Round 2 scores	4	3	4	4
SA3 - Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.				
	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4
Round 1 scores	4	2	3	3
Round 2 scores	4	3	3	4
SA4 - Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).				
	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4
Round 1 scores	4	2	2	4
Round 2 scores	4	3	3	4
SA5 - Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?				
	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4
Round 1 scores	4	3	4	3
Round 2 scores	4	4	4	3
<u>Final score</u>	<u>4</u>	<u>3.2</u>	<u>3.6</u>	<u>3.8</u>

Validity and Reliability of the Modified Scoring Rubric

Validity of a scoring rubric refers to the degree to which the inferences that are made of students' responses to the assessment are interpreted correctly and appropriately. According to Moskal & Leydens (2000), obtaining evidence on how a student will perform outside the school or in a different situation, criterion-related validity should be of concern (p. 3). Criterion-related concerns are associated with how the scoring criteria reflect the competencies that are being assessed and whether the measures or scoring levels are appropriate (Moskal, 2000, p. 4). The 2009 scoring rubric was shown to be applicable to all mechanics topics, including kinematics, Newton's laws of motion, work and conservation of energy, and levels of complexity of

problems (Docktor, 2009, p. 204). The modified rubric used in this study eliminated only one category (Physics Approach) from the original list of scoring categories. Physics Approach (PA) was highly correlated with Specific Application of Physics (SAP), but did not have a correlation with the other scoring categories, thereby suggesting that even without this category in the rubric, the others could be used independently (Docktor, 2009, p. 203). To ensure that criterion-related concerns were addressed, the adapted rubric was evaluated by experts through a consensus agreement process as described later in this section.

Rigorous credibility and trustworthiness demands for scoring assessments are based on the type of assessment in question: the scoring of multiple choice, standardized testing is expected to meet more rigorous demands of accuracy and consistency of scoring than that of complex performance assessments (Jonsson & Svingby, 2007). Establishing significance of correlation measures between scorers and measuring the degree to which scores can be attributed to common scoring rather than to error in scoring are considered essential for such assessments (Stemler, 2004). However, authentic assessments, or performance assessments, have been shown to benefit from explicitly stated scoring (also known as analytic scoring, Jonsson & Svingby, 2007, p. 131) rubrics with more than three levels (Wiggins, 1998; Moskal & Leydens, 2000).

Two types of reliability are discussed when using rubrics for scoring: intra-rater reliability and inter-rater reliability. Intra-rater reliability refers to a lack of consistency of a single rater over time in large numbers of scored assessments. In a review of over 200 articles discussing rubric based scoring, Jonsson & Svingby (2007) noted that establishing a scoring routine through training and using a rubric with explicitly defined levels for the scores can eliminate this type of a reliability concern. With respect to inter-rater reliability, consensus rating

was the most frequently used method of scoring. In the same review, the authors note that the consensus percentage of exact agreement varied widely (between 94% and 100%) and agreement within one or two score points was considered a good level of consistency across all types of assessments. Citing many research studies, Jonsson & Svingby (2007) note that with authentic assessments, acceptable scoring agreement or inter-rater reliability can be achieved by various acceptable means – training of raters, having two raters instead of more than two, benchmarks or instructor’s solutions and rubrics with detailed definitions for levels of scores (p. 135). Moskal & Leydens (2000) provide the following guidelines for improving inter-rater reliability: preparing well defined scoring categories, ensuring clear separation between the scoring categories, and checking the concurrence of scores given by two independent raters for the same assessment. This method of establishing rubric reliability for this study was designed with all the above considerations and met all those criteria.

An important distinction to be made is that the purpose of assessment (high-stakes testing or assessment of demonstrations of performance based on learning) and type of assessment (multiple-choice or authentic problem solving) drive the reliability issues that must be addressed. In order to ensure that criterion-related concerns were eliminated or reduced, the previously recruited experts were asked to help ensure alignment between the research questions and the categories in the rubric by providing a score based on their agreement and provide suggestions for change or comments indicating why they agreed. The score levels in each category were also rated by the experts for consistency of values, and, the consistency of interpretation of rubric in scoring student responses. The scoring rubric was provided to the experts, with instructions on rating the modified rubric categories and score values (*Appendix E*). The experts were asked to rate each of the score levels and associated definitions within the categories assessing students’

abilities using a scale of one to four. According to Moskal & Leydens (2000), ensuring that the scoring categories definitions align with the competencies being measured would alleviate criterion-related validity concerns. A rating of one implied “disagree”, two implied “somewhat disagree”, three implied “somewhat agree”, and four implied “agree”. Table 6 shows an example of the format provided to the experts with respect to the rubric associated with question prompt number two. A copy of the entire modified rubric as initially provided to the experts is attached in *Appendix E*. After two iterations of expert reviews, comments and revisions, consensus was reached in all the rubric categories with agree or mostly agree. A copy of the finalized rubric is attached in *Appendix F*.

The validity of the finalized rubric was further tested by having the experts apply the rubric in scoring student responses. A physics class in a high school within the school system (but not in the Academy) was used to seek student volunteers for taking the DNMC. Students were told that their participation was not tied to any assessment of their performance or grade in the class. Five students volunteered, and consent forms were handed out to those students. Students were asked to return the consent forms during the following class period when the DNMC was administered. At the next class period, students who had previously volunteered and returned the consent forms were asked to confirm their consent again verbally and by their signature on a separate consent form (*Appendix B*). All students participated in the problem solving activity in class, however, only the students who volunteered turned in their responses to the researcher. No names were included on the student responses thus maintaining student confidentiality and assurance that scores would not be correlated to the student who volunteered.

Table 6

Sample of Rubric Format Provided to Experts for Rating

<p>Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.</p>						
<p>SA3 - Ability to utilize relevant science content and practices necessary in the design of a solution.</p>						
<p><u>Definition: Specific Application of Physics</u> assesses a solver’s skill at applying the physics concepts and principles from their selected approach to the specific conditions in the problem. If necessary, the solver has set up specific equations for the problem that are consistent with the chosen approach. A <i>specific application of physics</i> could include a statement of definitions, relationships between the defined quantities, initial conditions, and assumptions or constraints in the problem (i.e., friction negligible, massless spring, massless pulley, inextensible string, etc.)</p> <p>Reviewers, please provide your rating of the definition stated above as it relates to SA3 and question prompt number 2: (scale of one to four)_____.</p>						
	5	4	3	2	1	0
SPECIFIC APPLICATION OF PHYSICS	The specific application of physics is appropriate and complete.	The specific application of physics contains minor omissions or errors.	Parts of the specific application of physics are missing and/or contain errors.	Most of the specific application of physics is missing and/or contains errors.	The entire specific application is inappropriate and/or contains errors.	The solution does not indicate an application of physics and it is necessary.
<p>Reviewers Please provide your rating that corresponds with the level of your agreement, and, suggestions, or comments.</p>						

After consensus was reached on the alignment of the rubric to the research questions and the score levels were deemed appropriate through consensus agreement, experts received a scanned copy of one student’s response for applying the previously prepared rubric to score the response. An instructor’s solution developed by physics educators was also provided to the experts to help them with the scoring (see *Appendix I*). Based on previously reviewed research, an acceptable score difference of one point was determined as acceptable for consensus. Experts reviewed, scored and described their scoring rationale for the first student response (SR1). On

tabulating the four sets of scores and comments, the experts reviewed each other's scores and arbitrated regarding whether to change the previous score given or revise it based on the other experts' rationale. On the first student response (SR1), the final mean score was 12 points on that student response, and the lowest score given by an expert was 11 points and the highest score given by an expert was 13 points. The next round of scoring involved achieving consensus on two additional student responses (SR2 and SR3). The same procedures were followed and after two iterations, consensus was achieved based on previously described criteria. This process was repeated on the fourth (SR4) and fifth (SR5) student responses until consensus was achieved, and resulted in a valid rubric for use in the research study.

Main Study

Data Collection

Participants

Participants in this study were a cohort of students enrolled in their senior year of the 2017 engineering program at the Academy. Eleven students participated in this study, ten males and one female. Seniors in the Academy take Pre-AP Algebra II, Pre-Calculus, AP Calculus AB, Engineering Explorations I and II, Engineering Methods, Physics and Chemistry during the previous years. Students' senior year coursework includes AP Calculus BC, Engineering Design, Engineering Economy, Engineering Research and Internship.

Collection of DNMC student responses

The validated DNMC and the scoring rubric were used for data collection. Upon approval from the Virginia Tech IRB and the Roanoke County School Research Review Board (*Appendix J*), the DNMC was administered to the senior class of students in the Academy. Following the same procedures used for the pilot study, students who volunteered were asked to complete the

consent forms with parental approval, and, the signature forms on the day of the administration of the DNMC (*Appendix J*). Students did not provide their names on the responses.

Scoring of DNMC – Interrater Reliability

The purpose of establishing interrater reliability is to demonstrate consensus among the raters. The 2009 rubric previously demonstrated that the multiple raters' scores on the original rubric and their interpretations of the same problem solution had acceptable consensus, and was significantly above the possibility of chance agreement (Docktor, 2009, p. 126). The training necessary for achieving reliability of scoring was also determined to be between thirty and thirty-five minutes (Docktor, 2009, p. 129). The recommended method of scorer training was to use individual student responses to be scored independently and then collaboratively with an iterative process of discussion and arbitration to achieve the desired level of consistency (Docktor et al., 2016). This was the method used in this study.

Two local scorers were solicited (via email using IRB approved language found in *Appendix J*) for scoring the student responses. The researcher determined that having local scorers was critical to the logistics and efficiency of training and scoring data from this study. Criteria for selection of scorers were: a) that they had at least five years teaching experience, b) held a teaching license to teach science, mathematics or technology education, and, c) held at least a master's degree in a STEM or STEM education discipline. Both scorers met the criteria as shown in Table 7.

Table 7

Criteria for Selection of Scorers

Criteria	Scorer 1	Scorer 2
At least five years teaching experience	✓	✓
Held a teaching license to teach physics, mathematics or technology education	✓	✓
Held at least a master's degree in a STEM or STEM education discipline	✓	✓

The two scorers who agreed to participate also signed consent forms indicating their consent (*Appendix J*). The process of ensuring inter-rater reliability between the scorers is described in the following paragraphs.

To begin, the scorers were provided with a copy of the DNMC, the instructor's solution, and the scoring rubric. The researcher explained the purpose of the research, the instruments being used, the DNMC question prompts and the instructor's solution to the scorers. One of the student responses from the pilot study was provided to the scorers and they were asked to score the response independently using the previously validated rubric. The scorers were then asked to confer with each other to discuss their ratings, and adjust their scoring based on that arbitration. When scorers were satisfied with their agreement on the score for the particular student response, a second student response was provided to each rater to score independently. Once completed, they were asked to confer with each other and arbitrate any differences in scoring. This was repeated once more with a third student response, where at this point scorers were in complete agreement on scores. The remaining three student responses from the pilot study were also

scored by the scorers, and where resulting scores were identical. At this stage the raters were sufficiently prepared to score the DNMC responses of this study.

The two scorers were given all eleven of the Academy student responses to be scored independently. The scorers met to confer with each other regarding their scores and made any final adjustments before submitting the scores. The scores in each category were then used for the data analysis.

Data Analysis

This non-experimental case study was based on a small sample (eleven participants) where the population mean was not known. The data collected was a score for each student, obtained using the scoring rubric for the DNMC solution. A student could earn between 0 and 25 points based on completion of DNMC, and this total score was used to indicate overall performance (OSS). This overall score is the combination of all five previously identified student abilities related to PS and CT. Descriptive statistics of the data are presented in Table 8. These data were analyzed using a one-sample t -test, where the population mean is unknown.

Table 8

Descriptive Statistics of the Dataset

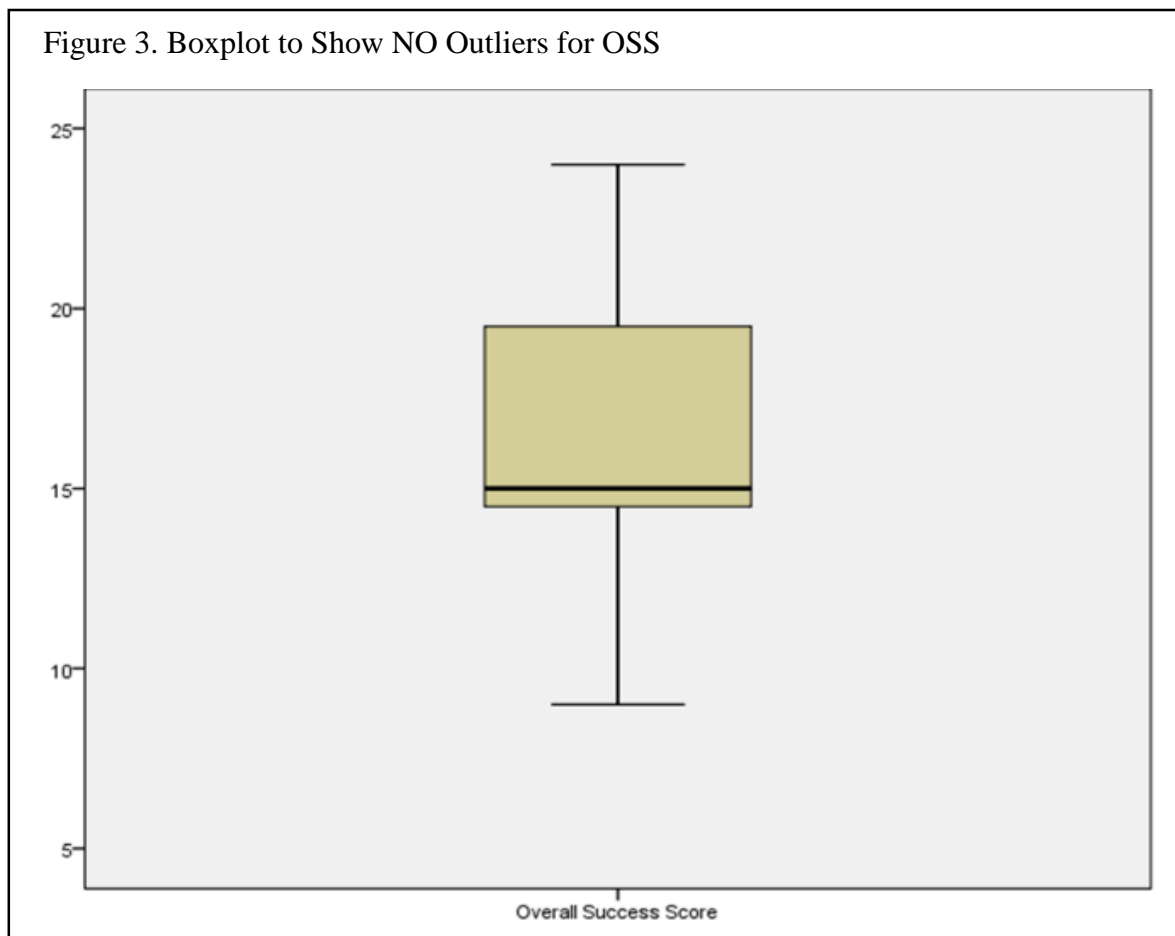
		95% Confidence Interval		
		Lower	Upper	
Overall Success Score	N	11		
	Mean	16.45	14.45	18.73
	Std. Deviation	3.984	2.146	4.967
	Std. Error Mean	1.201		

Results are based on 1000 bootstrap samples

The one-sample t -test is based on an assumption that the sample was drawn from a normally distributed population. Furthermore, the t -statistic can be compared with the t -

distribution whenever the sample size is large enough to produce a normal sampling of the mean (Howell, 2010). In the instance where the sample size is significantly smaller, i.e. less than 20, and the population distribution is unknown, the Shapiro-Wilk analysis of variance test for normality is used. The assumptions of the one-sample t -test are:

1. One dependent variable should be measured and tested. In this case the overall performance score for each student was used.



2. The data are independent or that they are not related to each other. In this study the data were from a single test and each data-point was from an independent source (student).
3. There should be no significant outliers. If there were outliers we would have had to make a decision about inclusion or exclusion of that data point. There were no outliers in the

data, as assessed by inspection of a boxplot for values greater than 1.5 box-lengths from the edge of the box.

4. The assumption of normality (Gaussian distribution) is necessary for the statistical significance testing (the *t*-test). However, the one-sample *t*-test is considered robust to violations of normality, and implies that some violation of this assumption is well tolerated by this test. For testing the normality of the sample, the Shapiro-Wilk analysis of variance test for normality was chosen because this test is effective for sample sizes less than twenty (Shapiro and Wilk, 1965, p 602). The null hypothesis of this test was that the population from which this sample is taken is normally distributed. For the chosen alpha level, with a significance (p-value) greater than the alpha level, we failed to reject the null hypothesis. The Shapiro-Wilk's test for normality results are found in Table 9

Test of Normality of Data.

	Shapiro-Wilk		
	Statistic	df	Sig.
Overall Success Score	.893	11	.152

OSS: Normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$).

One-sample *t*-test

The null hypothesis (H_0) for the one-sample *t*-test is $H_0: \mu = \mu_0$, where μ is the population mean as estimated from the current data, and μ_0 is the hypothesized population mean. In other words, this states that the estimated population mean is no different than the population mean. In the absence of a known hypothesized population mean, the researcher discussed the average performance for the class that participated in the pilot study with the teacher for that class. That average was used as the hypothesized population mean to test for significance in this study's data

analysis. The alternative hypothesis, $H_A: \mu \neq \mu_0$, states that the estimated population mean is not equal to the hypothesized population mean.

For purposes of this study, if we fail to reject the null hypothesis, it implies that students are performing at an acceptable average performance level. This will provide the explanation that students immersed in the integrative STEM ED pedagogical approach are able to perform at an average level that is acceptable to 9-12 educators. If we find that we reject the null hypothesis, it will be an indication that students are performing at a level below or above the mean. Below mean would provide an indication that we would need to examine our methodology for this study. Above mean indicates that students are performing above average and we would need to examine the effect size and the confidence interval associated with the effect size. In the one-sample t -test (see results in Table 10), we test the significance of whether the differences of means are real and not a random chance, and also, in order to discuss the size of this difference we use the effect size calculation.

Table 10

Test of Significance of the One Sample t-test

	t	df	Sig. (2-tailed)	Test Value = 12	95% Confidence Interval	
				Mean Difference	of the Difference	
					Lower	Upper
Overall Success Score	3.708	10	.004	4.455	1.78	7.13

Using the two-tailed t -test, we reject the null hypothesis, and conclude that the performance score (mean) of the sample population was statistically significantly higher by 4.455 (95% CI, 1.78 to 7.13) than the assumed normal performance score of 12, $t(10) = 3.708, p = .004$.

Bootstrapping

Bootstrapping is a statistical technique that creates from the sample population, a large number of repeated samples with replacement, and calculates the statistic on those samples (Efron, 1994, Cuming, 2014). The assumption of this technique is that the sample distribution is a good approximation of the population distribution (Cuming, 2014).

Table 11

One-Sample t-test using Bootstrapping

	Test Value = 12					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Overall Success Score	3.708	10	.004	4.455	1.78	7.13

The bootstrap data (using 1000 bootstrap samples) in Table 11, using the existing sample, was analyzed to obtain the more accurate results. Therefore a distribution of the t-statistic using the bootstrapped data provided more confidence to the *t*-test. SPSS provides the option to apply this technique for the *t*-test.

To determine the substantive importance or meaningfulness of these results, the effect size was calculated (Pedhazur and Schmelkin, 1991). To calculate an effect size, called *d* or Cohen's *d*, for the one-sample *t*-test, the mean difference is divided by the standard deviation of the difference using the formula for Cohen's *d*:

$$d = \frac{|M_D|}{SD}$$

M_D is the difference between the sample mean and the hypothesized mean, and SD is the standard deviation. According to Cohen (1988), effect size of about 0.2 is small, effect size of around 0.5 is medium and effect size of around 0.8 is large. According to the values reported

above, the calculated d value is 1.118 for this data sample. As this value is over .8, one can conclude that this effect size is large. However, based on the consideration of the one-sample t -test and the sample size, the effect size alone is not of major significance in this study (Cumming, 2014, p. 16). Based on the above analysis, there was a statistically significant difference between means ($p < .05$) and, therefore we reject the null hypothesis and accept the alternative hypothesis.

Investigation of the Relationship between the Dependent Variables

In order to answer research question two, this section describes the exploration of the correlational aspects of the five individual categories of the scoring rubric and the overall performance. The correlational coefficient is based on the statistic called the covariance (cov_{xy}) and is basically a number that reflects the degree to which two variables (X and Y) vary together.

The mathematical definition of covariance is:

$$cov_{xy} = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{N-1} : \text{where } N \text{ is the sample size.}$$

The data analysis to answer research questions 2a-e, the degree of variability of each of the category scores in the rubric with respect to the overall score was investigated. A positive covariance between SA1 (Useful Description) and OSS (Overall Success Score) implies that students who could successfully descriptively identify the salient information of the design challenge could also achieve success in solving the problem, or that students who are not successful with descriptively identifying the salient information in the problem, they are also not successful in solving the problem. This results from both of the variables having a negative variance. A negative covariance between SA1 and OSS implies that large positive values of one variable were paired with large negative values of the other. Finally in situations where there was no relationship between the two variables, the deviations from mean for the variables would be

positive about half the time and negative about half the time, resting in a near zero sum of covariance. When there is a strong positive covariance between the two variables, then cov_{xy} will be at its positive maximum and the Pearson Product-Moment (PPM) correlation coefficient (r) will be positive 1, and a strong negative covariance between the two variables will also correspond to cov_{xy} at its negative maximum with the PPM correlation coefficient (r) negative 1. When the two variables are perfectly uncorrelated, the PPM correlation coefficient and cov_{xy} will be zero.

Based on the above explanation, it could be inferred that we could use covariance as a measure of the strength of the relationship between the two variables. However, because covariance is a function of the standard deviations of the two variables, a high value of covariance could reflect a high correlation resulting from having small standard deviations, and a low correlation resulting from high standard deviations. To resolve this difficulty, the PPM correlation coefficient (r) is calculated by dividing the covariance by the product of the standard deviations of the two values.

Pearson Product-Moment Correlation - $r = \frac{cov_{xy}}{s_X s_Y}$

This PPM correlation coefficient is however, not a good estimate of the correlation coefficient of the population (denoted as rho – ρ). Particularly for small sample sizes, r is not a good estimate of the ρ (Howell, 2010, p. 253). An adjusted correlation coefficient (r_{adj}) is therefore calculated using the following formula:

$$r_{adj} = \sqrt{1 - \frac{(1-r^2)(N-1)}{N-2}}$$

This is the correlation coefficient reported in this study.

Summary of Research Method

To answer the research questions and the sub-questions, the data collected from the scored DNMC question prompts were examined using descriptive statistics, the one-sample *t*-test for testing the significance of the OSS, the covariance between each of the SA with the OSS and the strength of the correlation using an adjusted correlation coefficient. These statistical analyses helped obtain a snapshot of measures for CT and PS skills of students immersed in an I-STEM ED program with a small sample of students. The findings of the *t*-test to answer research question 1, and the covariance and strengths of correlation between the SA and the OSS to answer research question 2 are described and discussed in detail in chapter four.

CHAPTER FOUR: FINDINGS

The purpose of this study was to explore learning benefits that accrue from the use of the T/E DBL pedagogical approach within an integrative STEM education program. Specifically, to explore the use of this instructional strategy as a way to enhance students' critical thinking and problem solving skills. To provide evidence, data were collected on students' utilization of the design based approach, and acquired science and mathematics concepts in solving an authentic problem (DNMC) situated outside the confines of the classroom where those disciplines are taught. Two scorers trained on using the scoring rubric previously developed in the pilot study scored the students' written responses to the DNMC from the main study. The scores obtained were then analyzed to answer the following research questions (RQs):

1. In the context of an engineering program within a Governor's STEM Academy (Academy) employing the integrative STEM ED pedagogy, to what extent are students successful (Overall Student Success – OSS) in using engineering, science and mathematics for solving an authentic design-based problem outside the confines of the classroom where the subjects were originally taught?
2. How are the key student abilities in CT and PS correlated to overall student success (OSS)? Specifically what is the strength of the relationship of the following key student abilities (SA) with their success (OSS) in solving the authentic design-based problem:
 - a) Ability to organize essential information from a design challenge into appropriate and useful representations descriptively to guide the process of designing a solution.

- b) Ability to organize essential information from a design challenge into appropriate and useful representations graphically to guide the process of designing a solution.
- c) Ability to select and use relevant science content and practices necessary in the design of a solution.
- d) Ability to select and use relevant mathematics content and practices necessary in the design of a solution.
- e) Ability to demonstrate logical progression towards a solution.

The following sections present the analysis and findings of data collected in the order of the stated research questions.

Description of Sample

Eleven participants were involved in solving the DNMC (see Appendix G for DNMC student handout). Of the eleven students, one was a female and the remaining males, all aged between 17 years and 18 years. The students were seniors in the Governor's STEM Academy Engineering program and had completed all their coursework associated with the program as presented in Appendix A. Mathematics courses completed at the academy include Pre-AP Algebra II, Integrated Pre-Calculus, AP Calculus AB and AP Calculus BC, where the last three courses are also dual enrolled for college credit through the community college system. Science courses completed at the Academy include Advanced Chemistry and Integrated Physics, where Chemistry is also assessed through the Standards of Learning statewide exam. Engineering courses completed at the Academy include a series of progressively complex Career and Technology Education (CTE) courses – Introduction to Engineering I and II, Engineering Methods, Engineering Economy, Engineering Design, Engineering Research and Professional

Development, and Engineering Internship, and students also earn dual enrollment college credit for Engineering Methods (5 credits) and Engineering Economy (3 credits).

Data collection occurred during the last week of student attendance in the Academy. The qualitative data gathered from the eleven student responses to the DNMC were converted to quantitative data by two scorers trained using the previously developed modified rubric (Appendix F). The variables and associated scores are presented in Table 12. Student responses as documented on the handouts are attached in Appendix K.

Table 12

Summary of Quantitative Data Representing Student Responses to the DNMC

Participant	UDSA1 0 to 5	SkSA1 0 to 5	SAPSA3 0 to 5	AMSA4 0 to 5	LPSA5 0 to 5	OSS 0 to 25
Student 1	4	3	3	2	3	15
Student 2	4	4	4	4	5	21
Student 3	4	4	3	1	1	13
Student 4	4	3	1	1	1	10
Student 5	4	5	5	4	4	22
Student 6	3	3	3	3	3	15
Student 7	4	4	3	3	3	17
Student 8	4	3	3	2	3	15
Student 9	4	4	2	2	3	15
Student 10	4	4	5	5	5	23
Student 11	4	4	2	2	3	15
Average scores	3.91	3.73	3.09	2.64	3.09	16.45
Average Percent	78.2%	74.6%	61.8%	52.8%	61.8%	65.8%

Note. UDSA1: Student Ability – *Useful Description*; SkSA2: Student Ability – *Sketch*; SAPSA3: Student Ability – *Specific Application of Physics*; AMSA4: Student Ability – *Application of Math*; LPSA5: Student Ability – *Logical Progression*; OSS: *Overall Success Score*

Research Question 1: Overall Student Success in the Academy

Research Question 1 (RQ1) was associated with the overall success score (OSS) achieved by individual students on his or her written response to the DNMC. The responses were scored using the modified rubric tested and validated in the pilot study (described in the previous chapter). The rubric had five components associated with the problem-solving process: *Useful Description* – organizing information into descriptive written statements, *Sketch* – representing the useful information using a sketch with labels, *Specific Application of Physics* – recognizing and utilizing the content and practices of physics specific to the conditions in the problem, *Application of Mathematics* – recognizing and utilizing the content and practices of mathematics specific to the conditions in the problem, and *Logical Progression* – the overall communication of a logical reasoning pattern and statement of the solution to the problem. For scoring purposes, each component had a maximum score of five with each numerical value associated with a specific description in the rubric. The OSS was the sum of the five components mentioned above and served as an overall measure of the success of students in their hand-written solution of the problem. The RQ1 can be answered by comparing mean OSS of the students in the Academy with that of a hypothesized mean of students not within the program in the Academy.

The two-tailed one-sample *t*-test can be used to compare a mean value from a sample to a criterion measure (i.e., to some other value). The criterion measure may be known or hypothesized and the two-tailed test can provide statistical significance to the sample mean above or below the criterion measure. In this study the criterion measure was the mean OSS of the pilot study participants. The pilot study participants were not students in the Academy and were not in an immersive T/E DBL experience in their school. The mean OSS achieved by the

pilot study participants was 12 out of a total possible 25 points and was used as the hypothesized mean.

RQ1 seeks to discern if there a difference between the mean OSS of students in the Academy and those who are not within the Academy. The null hypothesis states that there is no difference in the mean overall success score between the two student groups. The alternative hypothesis states that there is a difference in the mean overall success score of students in the Academy and those who are not within the Academy. Therefore, a two-tailed one-sample *t*-test is used to determine whether there is a statistically significant difference between the mean OSS in the study sample and the hypothesized mean OSS. The one-sample *t*-test, as a null hypothesis significance test, indicates whether the differences between the means are real, but it does not indicate the size of the difference. To try to overcome this limitation, an effect size can be calculated. Cohen's *d*, is one type of effect size that attempts to determine the size of the difference between the two means (Pedhazur and Schmelkin, 1991). To calculate an effect size for the one-sample *t*-test, the mean difference is divided by the standard deviation of the difference using the formula for Cohen's *d*:

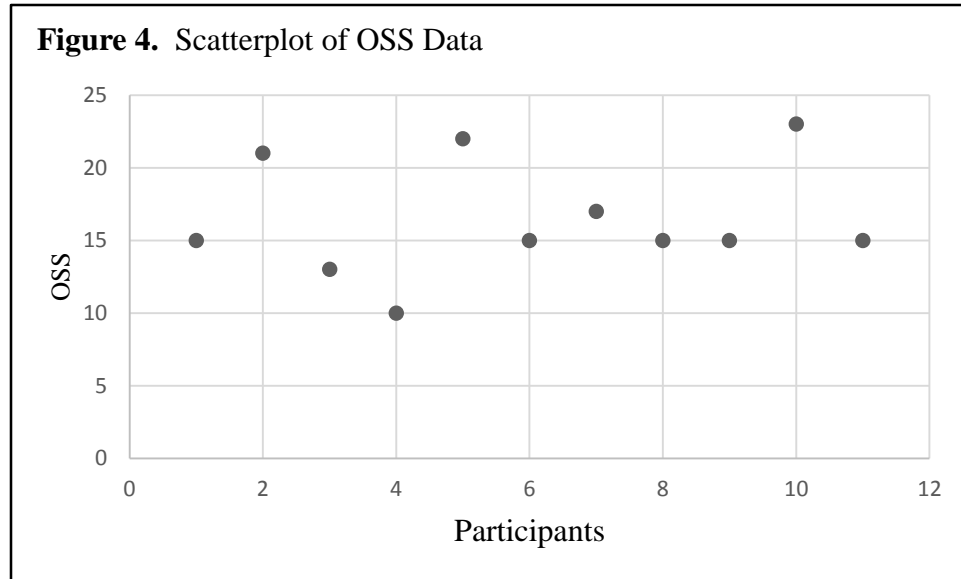
$$d = \frac{|M_D|}{SD}$$

M_D is the difference between the sample mean and the hypothesized mean, and SD is the standard deviation.

Requirements of the one-sample *t*-test

Prior to conducting the *t*-test, a critical part of the process involves checking to make sure that the data to be analyzed meet the following four assumptions. The first assumption is to ensure that the dependent variable (OSS in this case) is continuous. By definition, OSS was a continuous variable with a minimum score of zero and a maximum score of 25. The second

assumption is to ensure that each data point is not correlated to other data points for the variable being tested. In this study, all data were collected at one time and each student participant worked independently, and therefore the data points were not correlated. The third assumption is to ensure that there are no outliers in the data that would affect the results of the mean value in the *t*-test. The scatterplot presented in Figure 4 shows that there were no outliers for this variable.



The fourth assumption is to ensure that the data are normally distributed. The Shapiro-Wilk test for normality is recommended for small sample sizes. Shapiro-Wilk test is testing the null hypothesis that the data's distribution is equal to a normal distribution. Failing to reject the null hypothesis of the Shapiro-Wilk test as the significance value is greater than 0.05 (Table 13), the OSS scores from the main study were determined to be normally distributed ($p > .05$).

Table 13

Overall Success Score: Shapiro-Wilk Test for Normality

	Statistic	df	Sig.*
Overall Success Score (OSS)	.893	11	.152

* OSS were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$).

Bootstrapping using re-sampling

Due to the small sample size in this study, the bootstrapping technique was used to help develop better estimates of the population statistic using the re-sampling (with replacement) feature offered in SPSS statistical software to generate 1000 samples. Bootstrapping is a way of estimating statistical parameters (e.g. the population mean and its confidence interval) from the sample by means of resampling with replacement. Bootstrapping does not make any assumptions about the distribution of the sample, but the major assumption behind bootstrapping is that the sample distribution is a good approximation to the population distribution (Cumming, 2014). Table 8 in the Chapter Three (p. 58) provides descriptive statistics for the bootstrapped sample determined for this study. The sample mean of this sample was 16.45 with a standard deviation of 4.698.

One-Sample *t*-test Results

Results from the two-tailed one-sample *t*-test (Table 14), indicate that the mean OSS was statistically significantly higher by 4.455 (95% CI, 1.78 to 7.13) than the assumed normal performance score of 12, $t(10) = 3.708$, $p = .004$. The calculated effect size is 1.117 (Cohen's *d*), and, as this value is over 0.8, indicates the effect size is large.

Table 14

Results from the Two-tailed One Sample t-test for OSS

	Test Value (hypothesized mean) = 12 (Bootstrap = 1000 samples)			95% Confidence Interval of the Difference		
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Overall Success Score	3.708	10	.004*	4.455	1.78	7.13

* $p < .05$

Research Question 2: Relationships between SAs and OSS

To answer Research Question 2 (RQ2) and its sub-questions, a Pearson's product-moment (PPM) correlation was used to assess the relationship between the *Overall Success Score* (OSS) and each of the five student abilities (SAs) identified as the components of the problem solving process. The PPM is a measure of the strength and direction of the association between two variables. The correlation coefficient can take values from +1 to -1, which indicates a perfect positive (+1) or negative (-1) association. A correlation coefficient of zero (0) indicates no association. The magnitude of the Pearson correlation coefficient (r) determines the strength of the correlation. Although there are no hard-and-fast rules for assigning strength of association to particular values, some general guidelines are provided by Cohen (1988):

$0.1 < |r| < .3$ Small correlation

$0.3 < |r| < .5$ Medium/moderate correlation

$|r| > .5$ Large/strong correlation

where $|r|$ means the absolute value of r (e.g., $|r| > .5$ means $r > .5$ and $r < -.5$).

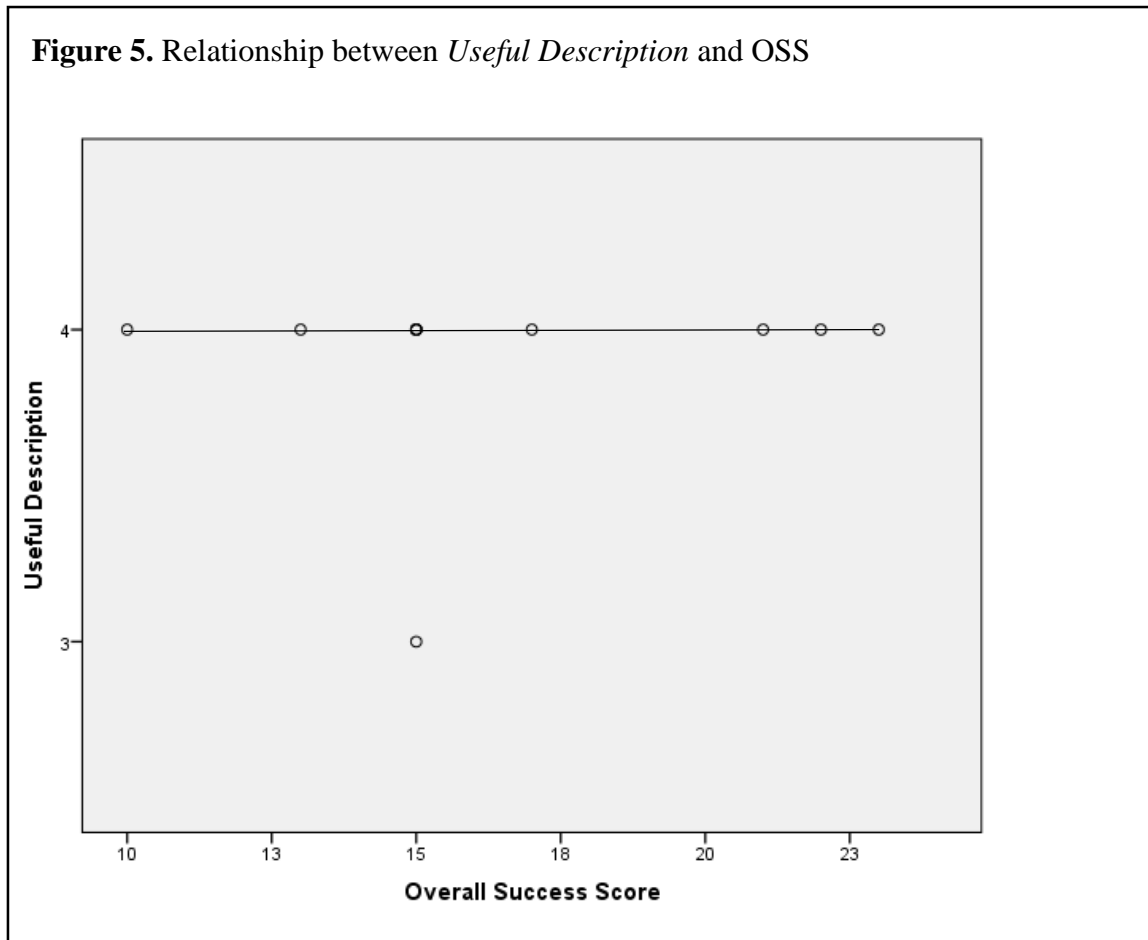
It is necessary to ensure that the data satisfy the assumptions underlying the PPM correlation calculations. The following section describes the data with respect to the five assumptions.

Determining Appropriateness of the PPM Correlation Statistic for the Data

It is only appropriate to use Pearson's correlation if the data pass each of the following five assumptions that are required for Pearson's correlation to provide a statistically valid result. The first two assumptions are associated with the variable types being continuous and existing for each of the sample data points. The previously described definitions of the five student ability variables (values between 0 and 5) and the overall success score (values between 0 and 25) are

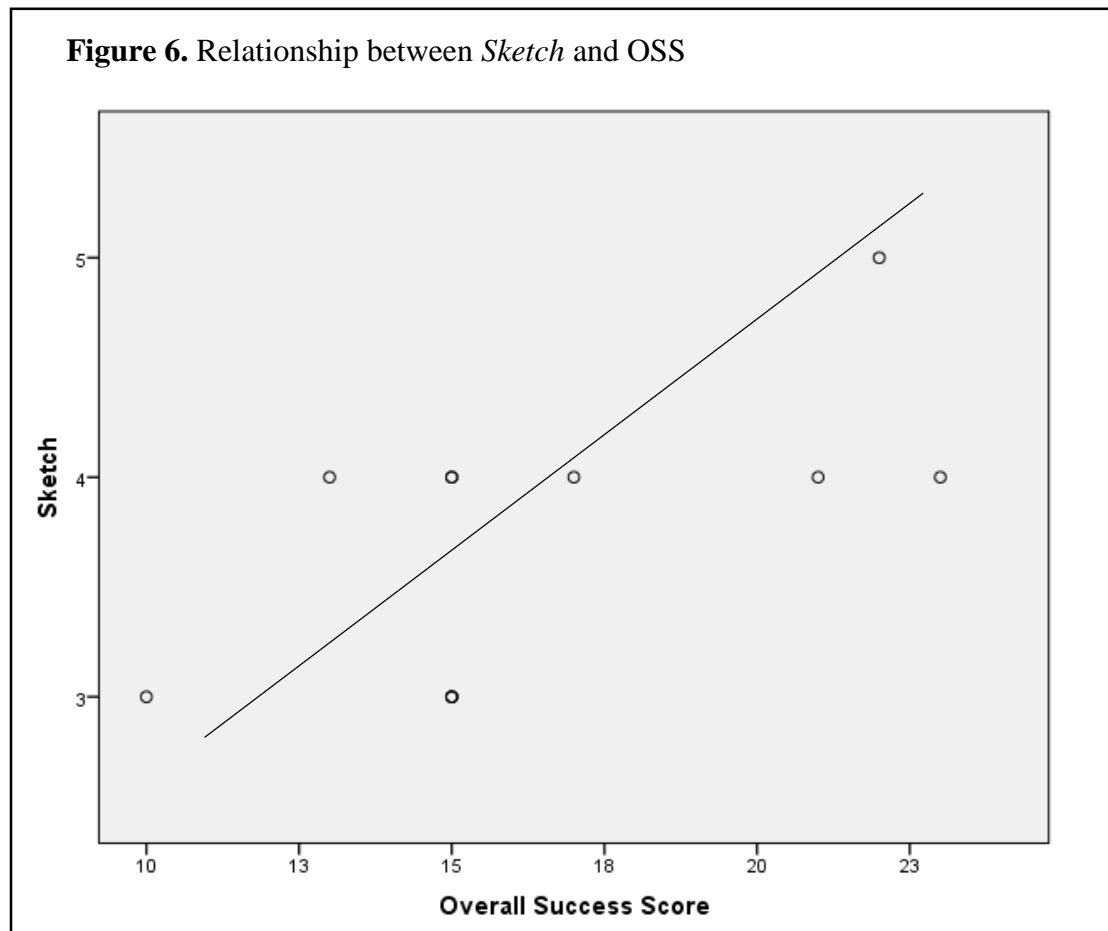
continuous within the stated range. For the dataset, there are no missing data (indicated by a score of zero) for any of the variables as shown in Table 12. Thus the first two assumptions are satisfied.

The third assumption is related to the existence of a linear relationship between the variables being paired and is presented using scatterplots.



The relationship between the variable *Useful Description* (UDSA1) and the OSS achieved by students as shown in Figure 5 indicates linearity, except for the outlying score (3 out of 5) achieved by Student 6 (Table 12) for UDSA1 with the OSS of 15. Three other students also achieved an OSS of 15 but each of those students earned 4 points for the *Useful Description* student ability thereby maintaining linearity. The scatterplot in Figure 2 also shows that the slope

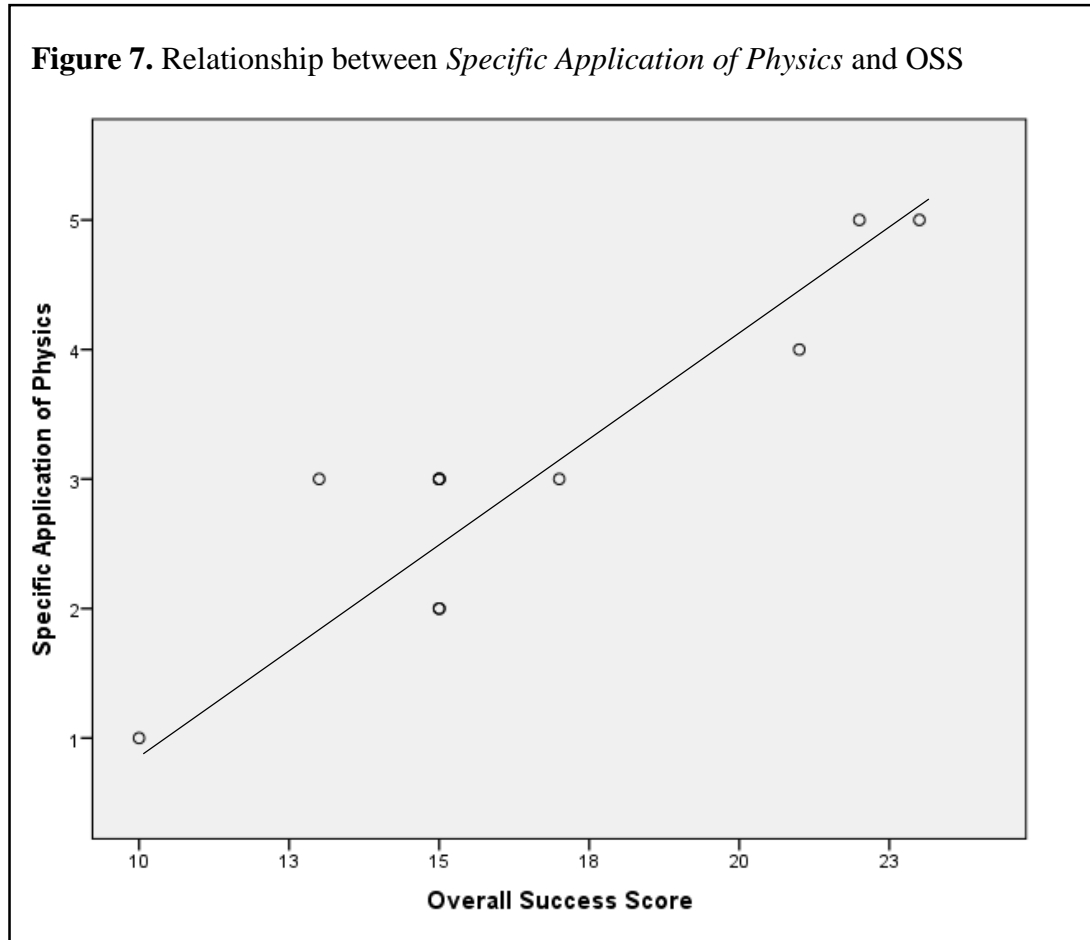
of the trend line is zero (ignoring the outlier) and therefore the linear relationship is horizontal in nature. The correlation coefficient is expected to be zero.



The relationship between the SA for sketching (SkSA2 for *Sketch*) and the OSS achieved by students as shown in Figure 6 indicates a linear trend with the slope of the trend-line greater than zero and therefore the linear relationship is positive in nature. The correlation coefficient is expected to be a positive value less than one.

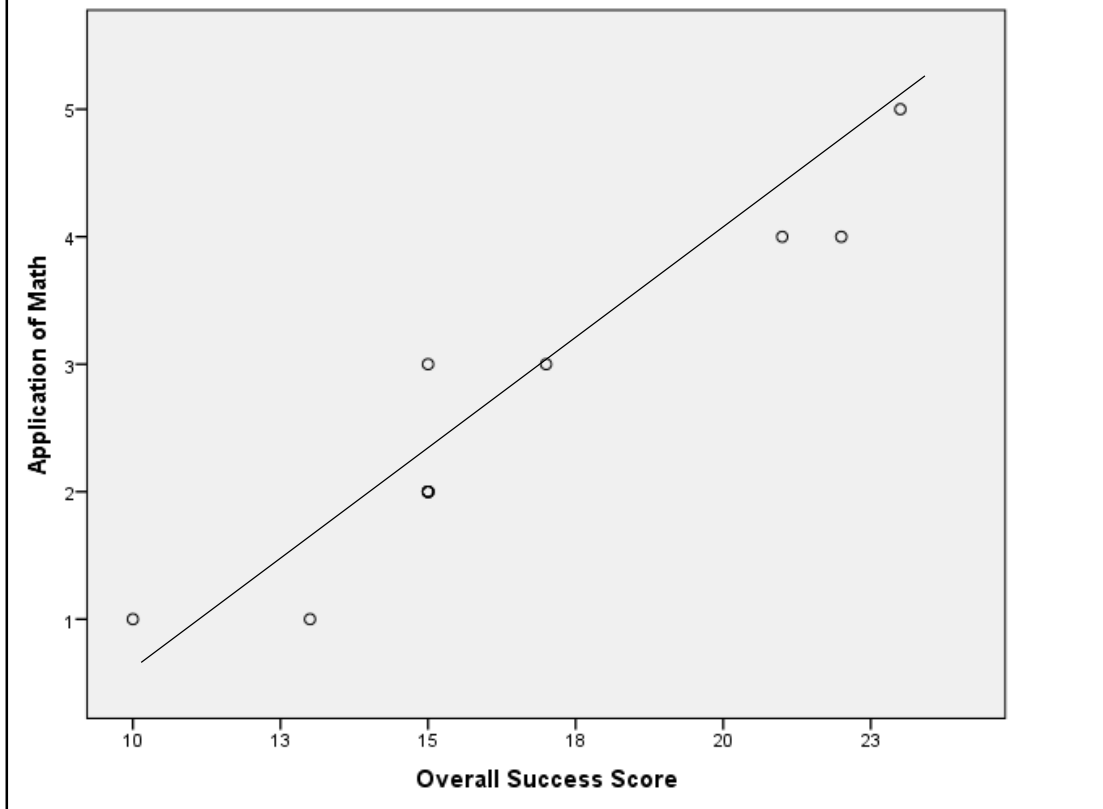
The relationship between the SA for recognizing and selecting physics content relevant to the problem (SAPSA3 for *Specific Application of Physics*) and the OSS achieved by students as shown in Figure 7 indicates linearity with the slope of the line greater than zero and therefore the

linear relationship is positive in nature. The correlation coefficient is expected to be a positive value less than one in this instance.



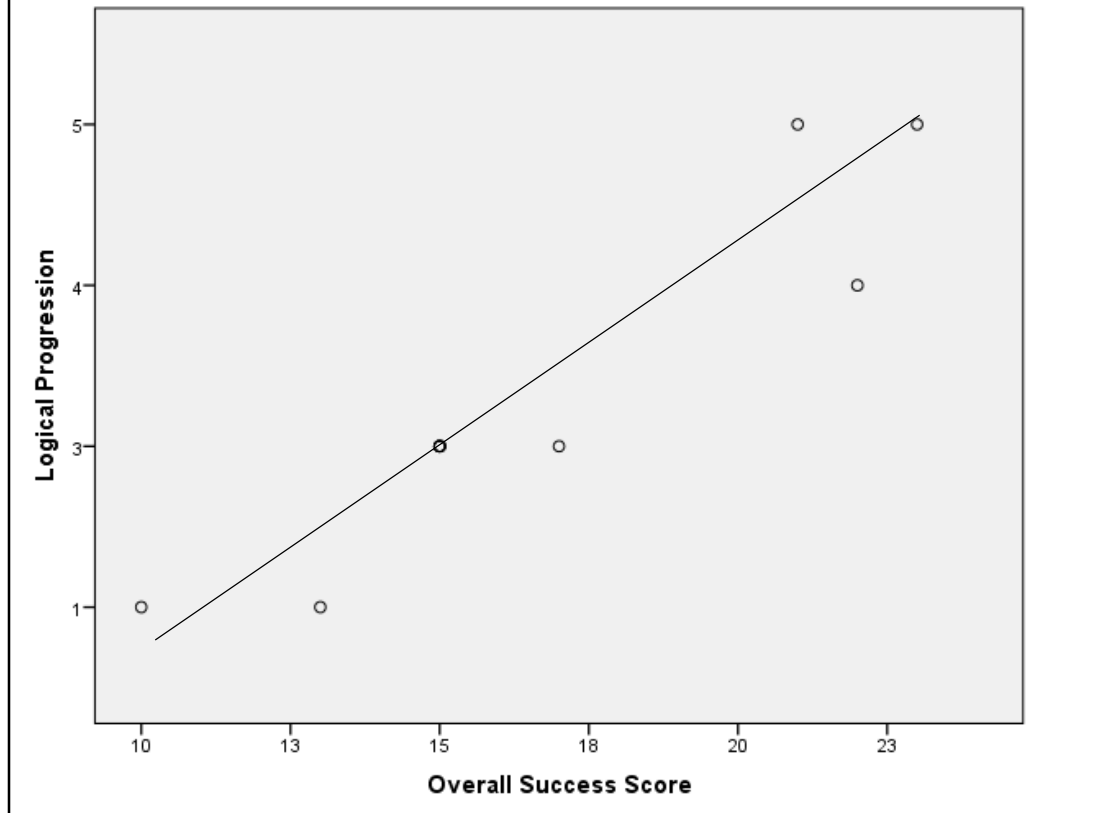
The relationship between the SA for recognizing and selecting mathematical content relevant to the problem (AMSA4 for *Application of Mathematics*) and the OSS achieved by students as shown in Figure 8 indicates linearity with the slope of the trend-line greater than zero and therefore the linear relationship is positive in nature. The correlation coefficient is expected to be a positive value less than one.

Figure 8. Relationship between *Application of Mathematics* and OSS



The relationship between the SA for *Logical Progression* (LPSA5) in designing a solution to the problem and the OSS achieved by students as shown in Figure 9 indicates linearity with the slope of the trend-line greater than zero and therefore the linear relationship is positive in nature. The correlation coefficient is expected to be a positive value less than one.

Figure 9. Relationship between *Logical Progression* and OSS



Further discussions of the specific strength of the relationships for each of the above relationships between the SA's and OSS are presented within the appropriate sub-sections.

The fourth assumption is related to the presence of outliers in the data points. Through visual inspection of scatterplots presented in figures two through six, it was determined that only the data point (Student 6 as shown in Table 12) for the variable associated with *Useful Description* (UDAS1) had an outlier which violated this requirement. However, there was no attempt made to remove the data point from the dataset because the slope of the linear relationship between *Useful Description* and the *Overall Success Score* is observed to be zero indicating no correlation.

The fifth assumption of normality of data was examined by conducting the Shapiro-Wilk test of normality for each of the variables. Table 15 presents the statistics from the Shapiro-Wilk

test. *Useful Description*, *Sketch* and *Logical Progression* violate assumptions of normality. These violations are considered during the discussion of findings for the specific sub-questions. As Pearson’s correlation is somewhat robust to deviations from normality, all the variables were considered for correlation to OSS (Pedhazur and Schmelkin, 1991).

Table 15

Shapiro-Wilk Test for Normality of data for the Student Abilities and OSS

<u>Student Abilities</u>	Shapiro-Wilk		
	Statistic	df	Sig.
Useful Description	.345	11	.000*
Sketch	.793	11	.008*
Specific Application of Physics	.912	11	.255
Application of Math	.919	11	.311
Logical Progression	.850	11	.043*
Overall Success Score	.893	11	.152

*Significance is less than 0.05 ($p < .05$), indicates data not normally distributed

The PPM correlation coefficient (r) is however, not a good estimate of the correlation coefficient of the population (denoted as rho – ρ). Particularly for small sample sizes, r is not a good estimate of the ρ (Howell, 2010, p. 253). An adjusted correlation coefficient (r_{adj}) is therefore necessary and was calculated using the following formula and reported in this study (Howell, 2010, p. 253):

$$r_{adj} = \sqrt{1 - \frac{(1-r^2)(N-1)}{N-2}}$$

It is also useful to look at the coefficient of determination, which is the proportion of variance in one variable that is explained by the other variable and is calculated as the square of the correlation coefficient (r^2). The coefficient of determination is also reported for each correlation.

Sub-question 2a: Restate Essential Information Descriptively

The *Useful Description* component assesses a solver's ability to glean information from the problem statement in the DNMC and organize the essential information into written statements. Targeted content includes specifying known information, assigning appropriate symbols for quantities, and stating goals or targets to determine benchmarks for success. This component is scored on six levels (zero to five), with each level described in detail in the scoring rubric (Appendix F).

A PPM correlation was calculated (Table 16) to test the strength of the correlation between the Overall Success Score (OSS) achieved by students and scores for their ability to organize essential information from a design challenge into appropriate and useful written descriptions (*Useful Description* or UDSA1). Based on the PPM, the small correlation between students' overall successful problem solving and their ability to provide a useful description of the problem was found to be statistically insignificant ($r = 0.121$; $p > .05$). The results indicate that students' ability to describe the problem in written statements was not correlated with their ability to successfully solve the problem. Calculation of the coefficient of determination was deemed unnecessary given the weak correlation.

Table 16

PPM Correlation – Students’ OSS and score for Useful Description

		Overall Success Score	Useful Description
Overall Success Score	Pearson Correlation	1	.121
	Sig. (2-tailed)		.723*
	N	11	11

* $p > .05$

Sub-question 2b: Organize Essential Information Graphically

The *Sketch* component assesses a solver’s ability to represent the information in the problem in a symbolic and graphical manner stating qualitative expectations and quantitative known values described in the problem. A sketch is an important visual interpretation in the problem solving process (Heller & Reif, 1984). This component is associated with six levels of the score (zero to five), with each level described in detail in the rubric for scoring purposes (Appendix F).

Students’ ability to organize essential information from the DNMC into appropriate and useful graphical representations was measured through a score for the *Sketch* (SkSA2). A Pearson's product-moment correlation was run to assess the relationship between OSS and SkSA2.

Table 17

PPM Correlation – Students' OSS and score for Sketch

	Overall Success Score	Sketch
Overall Success Score	Pearson Correlation	.635
	Sig. (2-tailed)	.036*
	N	11

* $p < .05$

Initial analysis showed the relationship to be linear, with the OSS variable normally distributed (SkSA2 violated the assumption of normality), as assessed by Shapiro-Wilk's test ($p > .05$). There was a strong positive correlation between students' ability to graphically represent useful information and their overall success score in solving the problem, $r = .635$, $p < .05$ (Table 17), with students' ability to sketch useful information explaining 40% ($r^2 = .403$) of the variation the overall success score. Given the small sample size, as previously noted, the adjusted correlation coefficient was calculated and shows a strong positive correlation as well ($r_{adj} = .581$).

Sub-question 2c: Select/Use Science Content and Practices

The *Specific Application of Physics* (SAPSA3) component reflects the process of selecting relevant physics principles and applying them to the specific context of the problem. This strategic planning process is typically difficult to assess as students often do not write down the principles or formulae and relate the quantities in the problem to the appropriate variables unless explicitly asked to do so. This category includes the identification of appropriate principles and concepts and the actual application of those principles to the specific conditions in the problem. This component is associated with six levels of the score (zero to five), with each level described in detail in the rubric for scoring purposes (Appendix F).

SAPSA3 variable is associated with students' ability to select and use relevant science content and practices necessary in designing the solution to the DNMC. The correlation of SAPSA3 with OSS was important in explaining the relationship of students' ability to recognize relevant science content and utilize appropriate practices with their overall success in designing a solution to the DNMC evidenced by that score.

Table 18

PPM Correlation – Students' OSS and score for Specific Application of Physics

		Overall Success Score	Specific Application of Physics
Overall Success Score	Pearson Correlation	1	.916**
	Sig. (2-tailed)		.000*
	N	11	11

** Correlation is significant at the 0.01 level (2-tailed).

* $p < .01$

Preliminary analysis showed the relationship to be linear with both variables normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$) with no outliers. The Pearson's Product-Moment correlation to assess the relationship between students' ability to select and utilize relevant science content and practices in designing a solution to the DNMC and the overall success score achieved showed that there was a strong positive correlation between the two variables, $r = .916$, $p < .001$ as shown in Table 18. Students' ability to select and utilize relevant science content and practices explained approximately 84% of the variation in the OSS (calculated by r^2). Given the small sample size, as previously noted, the adjusted correlation coefficient was calculated and shows a strong positive correlation as well ($r_{adj} = .821$).

Sub-question 2d: Select/Use Mathematics Content and Practices

The *Application of Mathematics* component assesses a solver’s ability to select and utilize appropriate mathematical content and procedures to complete the analysis for solving the problem. Content and procedures may include rules and strategies from algebra (e.g. solving equations, substitution, etc.), calculus (e.g. Chain Rule) or geometry (e.g. solving for angles or sides of triangles). This component is associated with six levels of the score (zero to five), with each level described in detail in the rubric for scoring purposes (Appendix F).

AMSA4 variable is associated with students’ ability to select and use relevant mathematical content and practices necessary in designing the solution to the DNMC. The correlation of AMSA4 with OSS was important in explaining the relationship between students’ ability to recognize relevant mathematical content and utilize appropriate practices and their overall success in solving the DNMC evidenced by that score.

Table 19

PPM Correlation – Students’ OSS and score for Application of Math

		Overall Success Score	Application of Math
Overall Success Score	Pearson Correlation	1	.953**
	Sig. (2-tailed)		.000*
	N	11	11

** Correlation is significant at the 0.01 level (2-tailed).

* $p < .01$

Preliminary analysis showed the relationship to be linear with both variables normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$), and there were no outliers. The Pearson's product-moment correlation to assess the relationship between students’ ability to

select and utilize relevant mathematics content and practices in designing a solution to the DNMC and the overall success score achieved showed that there was a strong positive correlation between the two variables, $r = .953, p < .001$ as shown in Table 19. Students' ability to select and utilize appropriate mathematical content and practices explained approximately 91% of the variation in the OSS ($r^2 = 0.908$). Given the small sample size, as previously noted, the adjusted correlation coefficient was calculated and shows a strong positive correlation as well ($r_{adj} = .898$).

Sub-question 2e: Demonstrate Logical Progression

The *Logical Progression* component is associated with a solver's ability to communicate reasoning and laying out a clear and focused strategy in achieving the goal. It means that the solution is coherent (i.e. solver's reasoning can be understood), internally consistent (i.e. no contradictions in the parts of the solution) and externally consistent (i.e. results agree with the qualitative expectations of the problem identified). This component is associated with six levels of the score (zero to five), with each level described in detail in the rubric for scoring purposes (Appendix F).

The LPSA5 variable is associated with students' ability to demonstrate a logical progression towards designing a solution to the DNMC. The correlation of LPSA5 with OSS was important in explaining the relationship between students' ability follow a logical progression of steps from start to finish and their overall success in solving the DNMC evidenced by that score.

Preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$) with no outliers. The PPM correlation to assess the relationship between students' ability to demonstrate logical progression towards

designing a solution to the DNMC and the overall success score achieved showed that there was a strong positive correlation between the two variables, $r = .918$, $p < .01$ as shown in Table 20.

Table 20

PPM Correlation – Students’ OSS and score for Logical Progression

		Overall Success Score	Logical Progression
Overall Success Score	Pearson Correlation	1	.918**
	Sig. (2-tailed)		.000*
	N	11	11

** Correlation is significant at the 0.01 level (2-tailed).

* $p < .01$

Students’ ability to demonstrate a logical progression towards designing a solution explained approximately 84% ($r^2 = 0.843$) of the variation in their overall success score. Given the small sample size, as previously noted, the adjusted correlation coefficient was calculated and shows a strong positive correlation as well ($r_{adj} = .826$).

Summary of findings

The analysis of data for RQ1 indicated that the average OSS for students immersed in the I-STEM ED pedagogical approach in the Academy was statistically significantly higher than the hypothesized normal performance score of students not in the Academy. The calculated effect size of 1.117 (Cohen’s d) indicates that the effect size is large. The analysis of data with respect to RQ2 for correlations indicated that only specific student abilities (*Sketching* with $p < 0.05$, *Specific Application of Physics*, *Application of Math* and *Logical Progression* with $p < 0.01$) are significantly correlated to the OSS achieved by the students in the Academy. Students’ ability to

organize and describe useful information in written statements was not correlated to their overall success score. Ability to organize essential information into graphical representations, ability to select and utilize science content and practices necessary to design a solution, ability to select and utilize relevant mathematical content and practices, and, ability to demonstrate logical progression towards the design of a solution were strongly positively correlated to their overall success score after adjusting for the small sample size used in this study.

The data on students' abilities associated with *Useful Description*, *Sketch* and *Logical Progression* violated the assumption of normality as shown in Table 15. The PPM correlation coefficient is considered to be robust for violations of this assumption and therefore the correlational analysis was conducted for these variables.

Further discussions on the conclusions that can be drawn from these findings, the implications derived from those conclusions, and resulting recommendations for future research are presented in the following chapter.

CHAPTER FIVE: CONCLUSIONS, IMPLICATIONS AND RECOMMENDATIONS

Presented in this chapter are conclusions drawn from the analyses of the data, implications thereof, and recommendations for future research. All conclusions and implications are most relevant to the specific and limited data collected from students of the Academy and the program as it currently exists in the Academy. The recommendations for further research stem from the specific inherent constraints of this study, and expansions of the design of this study to encompass a larger sample size and comparisons between various programs.

Conclusions

The primary conclusion is that students immersed in an integrative STEM education program performed significantly better (as assessed using their overall success score) in designing a solution to the design-no-make-challenge (DNMC) when compared with a the performance of students in a traditional classroom. A secondary conclusion of this study is that four specific student abilities (out of five identified and used in this research study) are strongly related to students' performance in authentic problem solving. The following sub-sections describe the conclusions in detail.

Research Question 1: Overall Performance of Students in the Academy

Research Question 1 (RQ1) was associated with measuring the extent to which students were successful in solving an authentic design-based problem. The overall performance of students was assessed by the overall success score (OSS) achieved on the written responses to the DNMC. The sum of the individual scores for the five components representing five key student abilities (SAs) identified as the essential aspects of problem solving and critical thinking (described more completely in Chapter Two, p. 40) resulted in the OSS. From the data presented in Table 12 (p. 68), students achieved an average score of 16.45 points (out of 25 possible points)

which represents a 65.8% score. The t -test results showed statistical significance to the higher mean overall performance score of students in the Academy (higher mean by 4.455; 95% CI, 1.78 to 7.13) when compared with a hypothesized mean which represented a 48% score (presented in Table 14, p. 77). The conclusion drawn from this result is that the students in the Academy had a higher mean performance score than the hypothesized mean used as a benchmark. The hypothesized mean was obtained from the pilot study conducted in a traditional classroom which was not within the Academy, where the students were completing the same physics course (using the same curriculum) as students in the Academy. The calculated effect size (Cohen's d) of 0.8 indicated a large effect (Table 14, p. 77), which implies that the strength of significance of the t -test is large enough to be practically significant.

Research Question 2: Correlations between Overall Performance and Student Abilities

Research Question 2 (RQ2) was aimed at investigating the strength of the relationships between students' overall performance (OSS) and each of the five key student abilities (SAs) in designing a written solution to an authentic problem as posed in the DNMC. What follows is a discussion of the conclusions drawn from the data analysis.

As previously discussed in Chapter Four, for a small sample size it is recommended that the adjusted correlation be calculated and used for interpretations of the strength of correlation between the two variables. The correlational statistic value greater than 0.5 indicates a strong correlation (Cohen, 1988). Table 21 summarizes the correlational strengths between the overall performance (OSS) and the five student abilities (SAs).

Sketch reflects a solver's ability to represent the information in the problem in a symbolic and graphical manner stating qualitative expectations and quantitative known values described in the problem. Student abilities associated with *Specific Application of Physics* and *Application of*

Mathematics, reflect a solver’s ability to select relevant physics and mathematical content or principles and applying them to the specific context of the problem. *Logical Progression* reflects a solver’s ability to communicate reasoning and laying out a clear and focused strategy in achieving the goal. These four SAs were strongly correlated to their overall performance (OSS)

Table 21

PPM Correlations between OSS and the five SAs

Research Question Number (RQ)	Student Ability (SA)	PPM Statistic (<i>r</i>)	Significance level	Adjusted correlation statistic (<i>r</i> _{adj})
RQ2a	<i>Useful Description</i>	0.121	0.723	N/A
RQ2b	<i>Sketch</i>	0.635	0.036*	0.581
RQ2c	<i>Specific Application of Physics</i>	0.916	0.000**	0.821
RQ2d	<i>Application of Mathematics</i>	0.953	0.000**	0.898
RQ2e	<i>Logical Progression</i>	0.918	0.000**	0.826

Note: *Significance at $p < .05$; **Significance at $p < .01$

in designing a solution to the DNMC (presented in the adjusted correlation statistic column in Table 21). The resulting conclusion drawn from this analysis is that these student abilities or skills are critical to students’ successful problem-solving in situations outside the context where the specific content was learned.

Contributions of Specific SA’s towards the Variability in Students’ Overall Performance

The coefficient of determination is calculated as the square of the correlation coefficient. This statistic represents the percent of the data points that are closest to the line of best fit in the model, and is a measure of how well the regression line represents the data. A higher coefficient is an indicator of a better goodness of fit and can provide a good indication of prediction of the

variations of one variable with respect to the other in the regression model (Howell, 2010). By no means is this an indication of causality, but it best represents a measure of variability in OSS that can be predicted by the variability of those SA's. The calculated coefficient of determination for each of the five correlational analysis is summarized in Table 22.

Table 22

Pearson's Correlations and Calculated Coefficient of Determination for the SAs

Student Abilities	PPM Correlation (<i>r</i>)	Coefficient of Determination (<i>r</i> ²)
Useful Description	0.121 (<i>p</i> > .05)*	0.015 (1.5%)
Sketch	0.635 (<i>p</i> < .05)	0.403 (40.3%)
Specific Application of Physics	0.916 (<i>p</i> < .01)	0.839 (83.9%)
Application of Mathematics	0.953 (<i>p</i> < .01)	0.908 (90.8%)
Logical Progression	0.918 (<i>p</i> < .01)	0.843 (84.3%)

*Correlation is not statistically significant at the .05 level

The most significant contributions of students' abilities attributable to their overall success in designing a solution to the DNMC (from the regression model) come from their ability to select and utilize relevant content and practices in science (84%) and mathematics (91%), and from their ability to logically progress through the process (84%) to design a solution to an authentic T/E design problem. These SA's were found to be strongly represented by the correlational (linear) model in this dataset (Table 21).

Implications

The conclusions presented in the previous section have direct implications for instruction in K-12 T/E design education, student learning and assessment, and engineering program design in secondary schools. One of the primary motivations for this research was the need for STEM literate graduates adequately prepared for the skills needed to tackle the challenges in the 21st Century. US students lag behind in science and mathematics literacy and many studies have linked the lack of preparation of students to use high school science and mathematics knowledge to high rates of attrition in STEM programs at the undergraduate level (NCES, 2012; Pope et al., 2015; Budney, LeBold & Bjedov, 1998; Steif & Dantzler, 2005).

The mean overall performance of students in the academy was shown to be statistically significant (Table 14, p. 77). The practical interpretation of this statistically significant difference does not necessarily mean that the students overall performance was good. The percentage score of mean OSS (65.8%) represents a C grade performance. The lowest OSS score achieved was 10 points (40% or F grade) and the highest was 23 points (92% or A grade). Nine of the eleven students in the sample achieved exactly or above passing grades (greater than or equal to 15 points or 60% and above). The implication from the above is that the average student success score in the Academy does not represent good performance in demonstrating problem solving skills on the DNMC. This lack of success could have many factors associated with it and additional discussions will follow in the next section on recommendations for future research investigations.

The correlational analysis between students' abilities and overall performance revealed that specific skills involving selecting and utilizing science and mathematics content and practices were statistically significantly related to the overall performance in designing a solution

to the DNMC provided. The implications from these results are that when designing a solution to the DNMC, students' abilities to recognize, recall, select and utilize science and mathematics content and practices are significant to successful T/E design-based problem solving (outside the confines of the classroom where the science or mathematics was learned) as implemented in this study using a DNMC. This finding may have broader implications for instruction, classroom assessment and student learning. However, further research will be needed to explore those avenues for improving student outcomes.

From a practical perspective, the low average (percentage) scores in the Specific Application of Physics (61.8%) and Application of Mathematics (52.8%) reveal that students in the Academy need to improve their ability to recognize, select and utilize relevant science and mathematics content and practices in designing a solution to an authentic T/E design-based problem (such as the DNMC). This could imply that instructional strategies need to be further strengthened to help students learn to select and utilize science and mathematics in problem solving in diverse contexts. There may be reason to also investigate the same skills in students in the lower grades to focus on helping develop these skills at an earlier grade level for all students. The statistically significant coefficient of determination (r^2) associated with the student abilities of *Specific Application of Science*, *Application of Mathematics* and *Logical Progression* in contributing to the variation of their *Overall Success Score* corroborates the importance of these student abilities in engineering design-based problem-solving.

The rubric developed in this study has the potential to be used as an assessment tool in the technology education classroom, and therefore this study has implications for demonstrating student growth. Teachers in Virginia are required to demonstrate student growth as a means of setting a performance goal for self-evaluation. Specific student abilities could be targeted or the

overall success score can be a benchmark for demonstration of student growth using pre- and post-assessments. While teachers in core disciplines use statewide testing for setting their performance goals, some Tech-ED teachers use industry credentialing for specific technology for their performance goals, teachers in those disciplines or subjects that do not have credentialing (such as engineering in high school) can use the modified rubric developed in this study to set up performance goals and indicators.

Recommendations for Further Research

This research was designed as a case study with a small convenience sample and therefore the conclusions cannot be generalized to other settings. The modified rubric and the DNMC developed in this study may have other uses in both Tech-ED classrooms and traditional classrooms, where engineering design is a component of the curriculum. Based on the findings, conclusions and implications of this study further research is needed in the areas of student learning and instruction, and assessment in technology education. The following sub-sections elaborate on each of those areas.

Student Learning and Instruction

The need for further research within technology education has been well documented by several researchers (Zuga, 1995, 2000; Cajas, 2000; Kolodner, 2000) and has been previously described in the literature review conducted for this study (presented in Chapter Two). This study generated preliminary and limited data on the benefits of the T/E DBL pedagogical approach within an integrative STEM education program as implemented in the Academy where engineering, mathematics and science courses are integrated and progressively sequenced within the four year curriculum. Further research on student learning, specifically 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. Such a study would potentially involve developing design-no-make challenges that are aligned with the four grade levels within the Academy. These challenges would have to be evaluated for grade-level alignment, validity and reliability by instructional experts in science, technology, engineering and mathematics. Next, a qualitative study protocol would need to be developed and implemented across the grades within the Academy using student volunteers who would participate in designing a T/E solution to the challenges assigned to their grade level. Pairs of students would be asked to think aloud during the process of designing their solutions and video-recorded for later transcription. Interviews of students following their completion of the task would help triangulate the data and add additional depth and clarifications. This procedure could be repeated with the same students at intervals through the course of a semester, year or program providing insight on student growth.

To expand the current study, a broader research design should include a comparison group with a similar number of students selected from a graduating class of students not immersed in an I-STEM ED experience. The expanded study should be designed to gather student preparation data using types of courses taken by these students so that they have the same number and type of mathematics courses (Algebra II, Pre-Calculus, AP Calculus AB and AP Calculus BC), and the same number and type of science courses (Pre-AP Physics, and Chemistry). Additional factors, such as age, grades achieved in the science and math courses, SAT scores, and SOL scores as self-reported by the students should be used as control factors in the two samples being compared. Furthermore, consideration should be given to the issue of student motivation in completing this assessment which has no bearing on their course grades.

Another suggested study could involve a longitudinal qualitative research design following-up on students graduating from the Academy over four years of their post-secondary endeavors. This study would potentially examine students' (a) persistence in a STEM field, (b) their self-efficacy and (c) perception of success in their post-secondary course of study or career choice. These snapshots over four years could provide insights that may help further the research base on the benefits of the type of Tech-ED program provided in the Academy.

An additional strand to follow would be to investigate teacher knowledge differences. Such a qualitative study could be focused on the investigation of the pedagogical approach and instructional strategies of Tech-ED teachers with an engineering background and those with a science background when they teach a specific pre-determined unit (e.g., wind-power or solar-power) in a Tech-ED classroom. The purpose of this study would be to understand how teacher education and content knowledge is related to instruction of the same specific unit of instruction. Assessment of students in these classrooms, by administering an appropriate DNMC and scoring the students' responses using the rubric developed in this study, could provide additional insights to the development of specific SAs in relation to the pedagogical approach and instructional strategies used in their respective classrooms.

Assessment in Tech-ED

In traditional Tech-ED classrooms, assessments are focused on the skills outlined as competencies in the CTE course framework (CTE, 2015). As previously noted (Chapter Two, p.28), a lack of focus on solving authentic problems is reflected in the competencies and therefore in the classrooms. In this study the DNMC handout and the modified rubric served as a method of assessment of problem solving skills. A suggested follow-up study could focus on creating templates for DNMC development and rubrics in order to add to the richness and

usefulness of CTE resources available for Tech-ED courses, and bring focus on solving authentic problems not currently addressed by the curricula. The rubric categories used to assess problem solving skills of students in this study could be further expanded for use by Tech-ED educators to prepare instructional goals for their teaching and also to assess their students' performance. Such a study could be designed to use a Delphi approach with disciplinary experts to develop content areas suitable for design-no-make challenges in the secondary school curriculum, and the related question prompts needed to effectively focus student thinking in the significant student abilities identified in this study.

Furthermore, the modified rubric could also be aligned for use with the design challenges developed. Such resources could help introduce the 21st Century skill of "Critical thinking and problem solving" (P21, 2015a) more effectively within traditional Tech-ED courses and in non-Tech-ED science classrooms where engineering design is introduced. Classroom teachers who are accustomed to using project-based learning would have a ready-to-use rubric without the time commitment involved in creating a method of assessing their assignments given to their students. Additional refinement of the modified rubric used in this study would be needed to ensure its usefulness in the sciences and technology education, along with a study to establish reliability of the rubric.

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Appendices

Appendix A: Academy Program Coursework and Sequence

	1 st Semester	2 nd Semester
9 th Grade	Introduction to Engineering I	Algebra 2
10 th Grade	Introduction to Engineering II	Integrated Pre-Calculus*
11 th Grade	Advanced Chemistry	Engineering Methods* Integrated Physics
		AP Calculus-AB*
12 th Grade	Engineering Economy*	Engineering Research & Professional Development
	Engineering Design	Engineering Internship
		AP Calculus-BC*

**Appendix B: Virginia Tech IRB and Roanoke County Public Schools: Pilot study approvals
and consent forms**

MEMORANDUM

DATE: February 16, 2017 

TO: John Wells, Susheela S Shanta

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Investigating and understanding High School STEM Academy Students Problem Solving Skills

IRB NUMBER: 17-126

Effective February 16, 2017, the Virginia Tech Institutional Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at: <http://www.irb.vt.edu/pages/responsibilities.htm>

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Expedited, under 45 CFR 46.110 category(ies) 5,7**
Protocol Approval Date: **February 16, 2017**
Protocol Expiration Date: **February 15, 2018**
Continuing Review Due Date*: **February 1, 2018**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future



ROANOKE COUNTY PUBLIC SCHOOLS

Department of Instruction & Technology

5937 Cove Rd. Roanoke, VA 24019 ♦ (540) 562-3900

Linda F. Wright, Ed.D.
Director of Elementary Instruction
ext. 10133 lfwright@rcs.k12.va.us

Rhonda Stegall, M.Ed.
Director of Secondary Instruction
Ext. 10131 rstegall@rcs.k12.va.us

February 20, 2017

Ms. Susheela Shanta

Dr. John Wells, Associate Professor
Virginia Tech
Integrative STEM Education

Dear Ms. Shanta and Dr. Wells:

After a thorough review of your request to conduct research in Roanoke County Public Schools, the Research Review Committee has approved your research project entitled "Investigating and Understanding High School STEM Academy Student Problem Solving Skills" to be conducted with teachers and students in Roanoke County Public Schools during the second semester of this school year. Permission to conduct this research is conditional on you receiving approval from Virginia Tech's Institutional Review Board (IRB) and on full compliance with the conditions and affirmations specified in the Application for Approval to Conduct Research you submitted along with your documentation. Please forward to this office a copy of your research results once completed.

Best wishes for a successful research project. Please let us know if we can provide further assistance.

Sincerely,

Rhonda W. Stegall

Rhonda W. Stegall
Director of Secondary Instruction

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Research Study Description and Informed Consent Form

IRB Study # 17-126

Title of Study: Investigating and understanding High School STEM Academy Student Problem Solving Skills

Research Investigators:

Virginia Tech

John Wells, Associate Professor, Integrative STEM Education (540-231-8471/jgwells@vt.edu)

Susheela Shanta, PhD Candidate, Integrative STEM Education (540-632-5517/sshanta@vt.edu)

I. General Information Regarding Research Studies

A research study is an organized investigation designed to reveal new information about a problem or question. The research goal of this study is to use the information gained from this study to improve our understanding of a specific aspect of teaching and learning. Below you will find details specific to this study. As a participant in this study, your consent and permission are required. Participation within this study is voluntary, and you may refuse to participate, or may withdraw your consent at any time for any reason, without penalty. If you have any questions on this study at any time, please do not hesitate to contact the researchers name above.

II. Purpose of this Research

The purpose of this study is to better understand learning outcomes of students that have been immersed in an instructional culture of using the content and practices of science and mathematics disciplines solve problems. In K-12 education integration of content and practices in the STEM fields provides opportunities for higher order learning because of higher cognitive demands in critical thinking and problem solving experiences. To conduct a study in this context, a problem statement (design-no-make challenge) will be provided to student participants and they will be asked to solve the presented problem and respond to the questions in the challenge. A scoring rubric will be used to score each response. A pilot study will be used to test the process of data collection and analysis with the goal of strengthening research design. Specifically, the purpose of this pilot study is to test the design challenge language, and the process of scoring the responses using a rubric.

III. Procedures

Upon receipt of this completed consent form, your child will be verbally asked to confirm his/her agreement to participate in this study and also asked to sign the consent form (see the second page). During the class period, the teacher will provide the design-without-make brief to the entire class as a learning activity. This activity will also assist the teacher in providing in-class review and remediation at a later date. The teacher will use your child's responses to work with the class to clarify any misconceptions and will review correct responses during a normal class period. Responses of the participants of this study, who have returned the consent form and confirmed their participation, will be copied while removing any identifying information from the response. The copies of your child's response will be provided by the teacher to the researchers without your child's identifying information (name) for purposes of conducting this study.

IV. Risks

There are minimal to no known risks associated with participation in this study. However, there is always some possibility that previously unknown or uncommon risks be associated with your child's participation within this study. Therefore, you should report any concerns to the researcher.

V. Benefits

There are no tangible or intangible benefits to your child for his/her participation in this study. This in-class activity will benefit all students through the normal instructional approach taken by the teacher. This research will instead contribute to the body of new knowledge regarding student outcomes of critical thinking and problem solving skills and methods of measuring the same.

VI. Compensation

Students participating in this problem solving session will not receive compensation.

VII. Confidentiality

No identifying information of your child will be associated with his/her response. The researchers will receive the responses of the participants with no identifying information on the documents. Furthermore, there will be no association of the teacher, class-period or school associated with any of the reports or papers. The consent forms will be the only documents on which there will be student names and these will be maintained by the researcher separately in a secure location for the duration of the study. At no time will the researchers release the raw data to anyone other than the research team. However, because the IRB is responsible for the protection of human subjects involved in research, it is possible that they may view this study's collected data for auditing purposes.

VIII. Freedom to Withdraw

Participants are free to withdraw from the study at any time without penalty. The teacher will retain the response of any student that chooses to withdraw at any time during the session.

IX. Subject's Responsibilities

My child will voluntarily agree to participate in this study. As a participant he/she will have to provide a written design-no-make challenge response or solution to the teacher. This response will be copied without his/her name on the response, and this will be provided to the researchers thereby ensuring that his/her identity is not associated with the response provided to the researchers.

X. Subject's/Parent's/Guardian's Permission

I have read the consent form and the conditions of this project. I have had my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.

Student's Name

Parent/Guardian of Participant

Date

Virginia Tech Institutional Review Board Project No. 17-128
Approved February 16, 2017 to February 15, 2018

ON THE DAY OF ADMINISTRATION OF DESIGN-NO-MAKE:

Confirmed Student's Verbal Consent? Circle the appropriate response Yes / No

Researcher's Initials: _____ **Date:** _____

I have read the consent form and the conditions of this project. I have had my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.

Student's Signature: _____ **Date:** _____

For questions or concerns about this research study, please contact Dr. John Wells (Virginia Tech) at 540-231-8471 or Ms. Susheela Shanta, (sshanta@rcs.k12.va.us), Teacher, RCPS at 540-632-5517.

A committee to protect your rights and welfare reviews all research on human volunteers. For questions or concerns about your/your child's rights as a human subjects participant, please contact:

David M. Moore
Chair, Virginia Tech Institutional Review
Board for Protection of Human Subjects
(540) 231-4991
moored@vt.edu
<http://www.irb.vt.edu>

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants

in Research Projects Involving Human Subjects

Title of Project: Investigating and understanding High School STEM Academy Student Problem Solving Skills

Investigator(s): Susheela Shanta, Researcher, sshanta@vt.edu, 540-632-5517

Dr. John Wells, jgwells@vt.edu, 540-231-8471

I. Purpose of this Research Project

The purpose of this study is to better understand learning outcomes of students that have been immersed in an instructional culture of using the content and practices of science and mathematics disciplines solve problems. In K-12 education integration of content and practices in the STEM fields provides opportunities for higher order learning because of higher cognitive demands in critical thinking and problem solving experiences. To conduct a study in this context, a design challenge (design-no-make challenge - DNMC) will be provided to student participants and they will be asked to solve the presented challenge/problem and respond to the questions in the challenge. A scoring rubric will be used to score each response.

A pilot study will be used to test the process of data collection and analysis with the goal of strengthening research design. Specifically, the purpose of this pilot study is to test the DNMC language, alignment of the questions within the DNMC with the research questions, and the process of scoring two student responses using a previously validated rubric. You are being asked to assist with this pilot study.

II. Procedures

Upon receiving this consent form as your agreement to participate in this study, you will be asked to review and comment on the DNMC. We will have a panel of four experts including you, to help with this pilot study. Your time commitment, which is expected to be two or three hours overall, is to assist in the following tasks:

1. Review the questions asked within the DNMC and ensure their alignment with the research questions. You will be asked to make comments and assign a score indicating your level of

- satisfaction with the version you reviewed. A scale of one to four (one being poor and four being excellent) will be used for each evaluation, and, suggestions for improvement or comments will be solicited. We will collect all the responses and make any needed adjustments for a second review by you in same manner. The goal is to have a score of three or more by all the experts in the reviews. If necessary, a third round of adjustments will be made and reviews solicited. Once the goal of a score of three or more by all of panelists is met, then the next step will be to review the rubric;
2. Review the rubric that will be used to score the student responses to the DNMC. The same process of review and adjustments, with the intention of evaluating the adequacy of the rubric for scoring the responses, and checking for alignment with the research questions stated in the study, will occur as in the previous review. The average score of three or more on a scale of four is the goal.
 3. Next, you will receive two student responses to the DNMC, and you will be asked to score them using the previously approved rubric. Any difficulties encountered during scoring will be discussed and adjustments to the DNMC and/or the scoring rubric will be made to alleviate those difficulties. These adjustments will be reviewed by all members of the panel and once agreement had been reached (using the one to four scoring method previously used), the pilot study will be concluded.

III. Risks

There are minimal to no risks associated with participation in this study. However, there is always some possibility that previously unknown or uncommon risks be associated with your personal participation within this study. Therefore, you should report any concerns to the researcher

IV. Benefits

There are no tangible or intangible benefits to you for your participation in this study. This research will instead contribute to the body of new knowledge regarding student outcomes of critical thinking and problem solving skills and methods of measuring the same.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

Your name and email address are the only identifying information associated with your participation in this pilot study. Only the researcher (Susheela Shanta) and the PI (Dr. John Wells) will have access to this information. Your electronic consent forms will be printed and maintained in a locked cabinet for the duration of this study. These will be destroyed after the completion of this study. Your emails will only be received by the researcher and will not be electronically shared with anyone else.

The returned DNMC and scored documents will also be maintained in a password protected computer. At

no time will the researchers release identifiable results of the study to anyone other than individuals working on the project, without your written consent.

The Virginia Tech (VT) Institutional Review Board (IRB) may view the study's data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

There is no compensation for your participation in this study.

VII. Freedom to Withdraw

It is important for you to know that you are free to withdraw from this study at any time without penalty. You are free not to answer any questions that you choose or respond to what is being asked of you without penalty.

Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject.

Should you withdraw or otherwise discontinue participation, you will be compensated for the portion of the project completed in accordance with the Compensation section of this document.

VIII. Questions or Concerns

Should you have any questions about this study, you may contact one of the research investigators whose contact information is included at the beginning of this document.

Should you have any questions or concerns about the study's conduct or your rights as a research subject, or need to report a research-related injury or event, you may contact the VT IRB Chair, Dr. David M. Moore at moored@vt.edu or (540) 231-4991.

IX. Subject's Consent

I have read the Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

_____ Date _____

Subject signature (please type in your name)

Subject printed name

For questions or concerns about this research study, please contact Dr. John Wells (Virginia Tech) at 540-231-8471 or Ms. Susheela Shanta, (sshanta@rcs.k12.va.us), Teacher, RCPS at 540-632-5517.

Email Recruitment of Experts

Hello _____!

Hope you are well.

I am working on lining up various aspects of my pilot study with the anticipation of completing my dissertation work by the coming summer. I will need help with reviewing a design challenge and related questions, to see if what I am trying to measure is aligned with the questions and problem-solving prompts. In addition, the rubric that will be used for scoring student responses needs to be also checked for alignment. I will explain the research questions and what I am trying to measure thoroughly after I complete my IRB protocol.

At this time I am only asking if you may be available to help with reviewing the above mentioned? I expect it would take about 2 to 3 hours overall (within 8 to 10 days) to complete the tasks. There will be 4 reviewers including you if you agree. I will send you more information and consent forms if you agree to help me.

Please let me know.

Thanks,

Susheela

Announcement to seek volunteers – Physics Class

At your next class you will be asked to solve a design challenge using your knowledge of physics and math. This is class work for all students, and your responses will help your teacher gain feedback on further instruction needed. We are requesting students to volunteer to allow us to use your responses to the design challenge for a research study that is aimed at better understanding learning outcomes of students that have been immersed in an instructional culture of using the content and practices of science and mathematics disciplines solve problems.

Today we are seeking student volunteers to provide their responses to the design challenge for the research study. If you volunteer to participate, your answer sheets will be copied without your name being identified with your response, and used for purposes of testing the design challenge. If you choose not to volunteer, your teacher will collect your response for instructional purposes, but not provide a copy to the researchers.

Again, you are free to choose to participate or not, and even if you choose to participate now, but change your mind later, there will be no repercussions. If you would like to volunteer, please raise your hand, and I will provide you with more information and a consent form that you need to take home with you. You will need to read over the form and have your parent/guardian read over it as well, sign in the appropriate places and bring it back with you next class.

Please note that everyone is going to work on this design challenge (as classwork) during the next class regardless of whether you participate in the study or not. If you volunteer for the study and return the paperwork provided by the next class, then the teacher will provide copies of your responses (without your name on the response) to researchers for the study.

Appendix C: Description of Study Provided to Experts

Background

The need for science, technology, engineering and mathematics (STEM) literate citizens in the 21st century is well documented (ITEEA, 2000, NAE and NRC 2002, NGSS, 2013). U.S. competitiveness in the global economy depends on the development of a workforce with knowledge and skills to tackle complex technological problems (Katehi, Pearson and Feder, 2009). In this changing, fast-paced, global economy, graduates need to know how to make complex arguments and solve problems they have never seen before (Ripley, 2013, Friedman, 2005). In response to the need for a STEM literate workforce equipped with 21st century skills, there is a push for K-12 educational reform to prepare students adequately to fill the need. 21st century skills have been identified as critical thinking, problem solving, communication, collaboration and creativity (P21, 2015a). STEM literacy has been described as the ability to use concepts in science, technology, engineering and math in solving human problems in a collaborative manner (NRC, 2009). The development of standards for technological literacy, the inclusion of engineering in science education, and the call for interconnectedness of the disciplines in STEM education are all efforts to reform education to meet the 21st century needs (ITEEA, 2000; National Science Board, 2007; NRC, 2009).

In contrast to the 21st century needs mentioned above and the efforts at educational reform over the last thirty years, US students continue to perform close to the bottom of the list in international assessments when compared with thirty industrialized countries in the world (NCES, 2012; Pope, 2015). Data from the Trends in International Mathematics and Science Study (TIMSS) and Program for International Student Assessment (PISA) show that US students continue to lag behind in mathematics and science literacy (NCES, 2012). The TIMSS and the PISA are designed to measure literacy in these subject areas rather than curriculum based content knowledge. Therefore, students' abilities in utilizing their knowledge in these subject areas for problem solving in other contexts (i.e. outside the confines of the specific classes) are targeted (NCES, 2012; Pope, 2015). These measures are more relevant than other in-school standardized testing, as these assessments require students to access their resident knowledge to solve problems outside the context of the classroom where the subject is being taught.

Purpose

Desirable learning outcomes are when students are able to gain a deeper 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. This is the goal of Integrative STEM Education, which 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 and Ernst, 2012/2015).

In K-12 education, the implementation of an integrative STEM education approach is best suited to a technology education program (Wells, 2015). In Virginia, this includes a series of sequential courses with progressively more complex content from the existing curriculum framework outlined in Career and Technology Education (CTE) guidelines of the Department of Education (DOE). CTE courses are designed to provide an opportunity for teachers to engage students in designing solutions to complex problems through research and discovery. These

courses are not required for graduation, fall under the category of electives, and thus, compete with AP coursework that students find more desirable. While AP courses are considered desirable from the perspective of college admissions, AP courses have not been shown to benefit students in developing critical thinking and problem solving skills (Pope, 2013, 2015).

Engineering (through its characteristic design-based pedagogical approach) offers a platform in K-12 education for integration of content and practices in the STEM fields, and provides opportunities for higher order learning because of higher cognitive demands in critical thinking and problem solving experiences ((NAE and NRC, 2014; Katehi, Pearson and Feder, 2009; Shepard, Colby, Macatangay and Sullivan, 2006; Wells, 2016). K-12 engineering programs (such as those within Governor’s STEM Academies in Virginia) may help bridge the gap previously discussed between high school curriculum (identified by US students’ poor performance in international testing), and the need for students to demonstrate STEM literacy outside the confines of the classroom. On the surface, it appears that these programs may have the potential, through the innovative approach to blending core courses (math and science), and design courses (CTE based courses) to create the opportunity for students to be engaged in the integrative STEM pedagogical approach to learning in 9-12 education in the “natural intersections of learning within the continuum of content areas” (Wells and Ernst, 2012/2015). It would therefore be appropriate to investigate the value of such experiences by gathering evidence on student learning outcomes in such programs (Wells, 2010; Zuga, 2001). The fundamental research question to be addressed by this study is: To what extent does the integrative approach to teaching science and math courses concurrently with engineering and technology in a STEM Academy enhance students’ problem solving skills (evidenced by their solutions to a problem requiring the utilization of science and math concepts and practices) outside the context of the science and math classroom? In order to conduct the research study described above, it will be beneficial to conduct a pilot study to refine the measurement instruments and methods.

Purpose of the Pilot Study

A pilot study will be useful to align the question prompts in the Design-No-Make Challenge (DNMC) used to measure the problem solving skills with the research questions, align the scoring rubric with the research questions and the DNMC question prompts, and also establish reliability (among scorers) of scoring student responses. The purpose of this pilot study is twofold:

- 1) Finalize the design brief and the question prompts that will be used in the study. The draft design brief will be circulated among five experts with background in integrative STEM education and/or Physics education.
- 2) Finalize the scoring rubric for scoring the DNMC student responses by aligning with the research questions and with the question prompts in the DNMC.
- 3) Establish reliability by using the rubric to score five student responses and achieve consensus among the experts on the scores.

Appendix D: Instructions to Experts, Research questions and draft DNMC with question prompts

Review packet

In our study, we are investigating students' problem solving skills when they are presented with an authentic problem in the domains of physics and mathematics. The specific **Student Abilities (SA)** of interest are described as follows:

1. Ability to organize essential information from a design challenge into appropriate and useful representations symbolically and visually, to guide the process of designing a solution.
2. Ability to recognize science content and practices necessary in the design of a solution.
3. Ability to recognize mathematics content and practices necessary in the design of a solution.
4. Ability to demonstrate logical progression towards a solution.

These SA are associated with the four questions that follow the Design-No-Make-Challenge (DNMC) as stated in the next two pages. The DNMC and questions (**in black**) will be provided to the students and they will be asked to respond to the questions asked.

Please read the DNMC scenario and challenge. Then for each question asked, please note (**in green**) my statement of correspondence with the SA number. **In red**, please note that you are requested to provide a score of 1 to 4 simply indicating your level of agreement. Then you are requested to provide your comments and any suggestions for improvement of the question. You may type your response in below the **Reviewer response** instruction.

Design-Without-Make Challenge (DNMC)

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the Sears Warehouse website information provided in the attachment.

Reviewers:

Chose a number between 1 and 4 for your responses and then provide comments. 1 implies you disagree, 2 implies you somewhat disagree, 3 implies you somewhat agree, and 4 implies you agree.

1) Part a - What is your understanding of the challenge described above? Describe using a few sentences.

Part b - Draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.

This question corresponds with Student Ability (SA) #1 as stated in the Student Abilities:

Ability to organize essential information from a design challenge into appropriate and useful representations symbolically and visually to guide the process of designing a solution.

Reviewer response: Do you agree with the correspondence between the question asked and the SA#1 as stated above? Please choose a number between 1 and 4 based on your level of agreement.

Enter your choice here: _____

Please provide comments and/or suggestions to help improve the question.

2) What physics formula(s) will you use in determining the power of the water pump? Explain your strategy in a few sentences.

This question corresponds with Student Ability (SA) #2 as stated in the Student Abilities:

Ability to recognize science content and practices necessary in the design of a solution.

Reviewer response: Do you agree with the correspondence between the question asked and the SA#2 as stated above? Please choose a number between 1 and 4 based on your level of agreement.

Enter your choice here: _____

Please provide comments and/or suggestions to help improve the question.

3) Set up your formula(s) to solve for the unknown, show your calculations, and any unit conversions you need to help you determine the power of the pump.

This question corresponds with Student Ability (SA) #3 as stated in the Student Abilities:

Ability to recognize mathematics content and practices necessary in the design of a solution.

Reviewer response: Do you agree with the correspondence between the question asked and the SA#3 as stated above? Please choose a number between 1 and 4 based on your level of agreement.

Enter your choice here: _____

Please provide comments and/or suggestions to help improve the question.

4) Using the results of your calculations, state the power of the motor you need. Using the Sears Warehouse information provided, which motor would you pick? How much will it cost you?

This question corresponds with Student Ability (SA) #4 as stated in the Student Abilities:

Ability to demonstrate logical progression towards a solution.

Reviewer response: Do you agree with the correspondence between the question asked and the SA#4 as stated above? Please choose a number between 1 and 4 based on your level of agreement.

Enter your choice here: _____

Please provide comments and/or suggestions to help improve the question.

Appendix E: Instructions and Modified Rubric provided to Experts

Scoring Rubric to rate student responses to DNMC

In our study, we are investigating students' problem solving skills when they are presented with an authentic problem in the domains of physics and mathematics. The specific **Student Abilities (SA)** of interest are described as follows:

5. Ability to organize essential information from a design challenge into appropriate and useful representations symbolically and visually, to guide the process of designing a solution.
6. Ability to utilize science content and practices necessary in the design of a solution.
7. Ability to utilize mathematics content and practices necessary in the design of a solution.
8. Ability to demonstrate logical progression towards a solution.

These SA are associated with the four questions that follow the Design-No-Make-Challenge (DNMC) previously reviewed. The following pages have the rubric for scoring the responses to the questions asked in the DNMC. The rubric has been adapted from Dr. Jennifer Docktor's dissertation in developing a problem solving assessment for physics. For her dissertation, Docktor revised a problem solving scoring rubric to evaluate written solutions to physics problems, and, obtained evidence for reliability and validity of the rubric. The rubric identifies general problem-solving processes and defines the criteria to attain a score in each: useful description, specific application of physics, math procedures, and logical progression. The instrument was tested in several physics problem solving events and the researchers concluded that rating written student solutions of classroom problems using the problem solving rubric gives an accurate view of their problem solving processes (Docktor, 2009).

Reviewers are asked to read the question (you helped craft during this last week) and the scoring rubric associated with the question, and indicate your level of agreement by typing a score between 1 and 4 under the descriptions for the scores under each of the four questions. As before, 1 implies you disagree, 2 implies you somewhat disagree, 3 implies you somewhat agree, and 4 implies you agree.

References

Docktor, J. & Heller, K. (2009). Robust assessment instrument for student problem solving. Proceedings of the 82nd NARST Annual International Conference, Garden Grove, California. (S2.2 Symposium: Multiple Perspectives on Problem Solving in Physics)

Scoring Rubric

Score	5	4	3	2	1	0
<p>1. Organization of essential information from a design challenge into appropriate and useful representations descriptively and visually, to guide students in the process of designing a solution</p>						
<p><i>Useful Description</i> assesses a solver’s skill at organizing information from the problem statement into an appropriate and useful representation that summarizes essential information symbolically and visually. The description is considered “useful” if it guides further steps in the solution process. A <i>problem description</i> could include restating known and unknown information, assigning appropriate symbols for quantities, stating a goal or target quantity, a visualization (sketch or picture), stating qualitative expectations, an abstracted physics diagram (force, energy, motion, momentum, ray, etc.), drawing a graph, stating a coordinate system, and choosing a system.</p>						
<p>USEFUL DESCRIPTION & SKETCH</p>	<p>5</p> <p>The description is useful, appropriate, and complete.</p> <p>The sketch is appropriate and complete.</p>	<p>4</p> <p>The description is useful but contains minor omissions or errors.</p> <p>The sketch is useful but contains minor omissions or errors.</p>	<p>3</p> <p>Parts of the description are not useful, missing, and/or contain errors.</p> <p>Parts of the sketch are not useful, missing, and/or contain errors.</p>	<p>2</p> <p>Most of the description is not useful, missing, and/or contains errors.</p> <p>Most of the sketch is not useful, missing, and/or contains errors.</p>	<p>1</p> <p>The entire description is not useful and/or contains errors.</p> <p>The entire sketch is not useful and/or contains errors.</p>	<p>0</p> <p>The response does not include a description.</p> <p>The response does not include a sketch.</p>
<p>Reviewers suggestions, comments, & score on level of agreement</p>						
<p>2. Ability to utilize relevant science content and practices necessary in the design of a solution.</p>						

Specific Application of Physics assesses a solver’s skill at applying the physics concepts and principles from their selected approach to the specific conditions in the problem. If necessary, the solver has set up specific equations for the problem that are consistent with the chosen approach. A *specific application of physics* could include a statement of definitions, relationships between the defined quantities, initial conditions, and assumptions or constraints in the problem (i.e., friction negligible, massless spring, massless pulley, inextensible string, etc.)

	5	4	3	2	1	0
SPECIFIC APPLICATION OF PHYSICS	The specific application of physics is appropriate and complete.	The specific application of physics contains minor omissions or errors.	Parts of the specific application of physics are missing and/or contain errors.	Most of the specific application of physics is missing and/or contains errors.	The entire specific application is inappropriate and/or contains errors.	The solution does not indicate an application of physics and it is necessary.
Reviewers suggestions, comments, & score on level of agreement						

3. Ability to utilize mathematics content and practices necessary in the design of a solution.

Application of Mathematics assesses a solver’s skill at following appropriate and correct mathematical rules and procedures during the solution execution. The term *mathematical procedures* refers to techniques that are employed to solve for target quantities from specific equations of physics, such as isolate and reduce strategies from algebra, substitution, use of the quadratic formula, or matrix operations. The term *mathematical rules* refers to conventions from mathematics, such as appropriate use of parentheses, square roots, and trigonometric identities. If the course instructor or researcher using the rubric expects a symbolic answer prior to numerical calculations, this could be considered an appropriate mathematical procedure.

Appendix F: Final Modified Rubric

	5	4	3	2	1	0
APPLICATION OF MATHEMATICS	The mathematical procedures are appropriate and complete.	Appropriate mathematical procedures are used with minor omissions or errors.	Parts of the mathematical procedures are missing and/or contain errors.	Most of the mathematical procedures are missing and/or contain errors.	All mathematical procedures are inappropriate and/or contain errors.	There is no evidence of mathematical procedures, and they are necessary.
Reviewers suggestions, comments, & score on level of agreement						
4. Ability to demonstrate logical progression towards a solution.						
<p><i>Logical Progression</i> assesses the solver's skills at communicating reasoning, staying focused toward a goal, and evaluating the solution for consistency (implicitly or explicitly). It checks whether the entire problem solution is clear, focused, and organized logically. The term <i>logical</i> means that the solution is coherent (the solution order and solver's reasoning can be understood from what is written), internally consistent (parts do not contradict), and externally consistent (agrees with physics expectations).</p>						
	5	4	3	2	1	0
LOGICAL PROGRESSION	The entire problem solution is clear, focused, and logically connected.	The solution is clear and focused with minor inconsistencies	Parts of the solution are unclear, unfocused, and/or inconsistent.	Most of the solution parts are unclear, unfocused, and/or inconsistent.	The entire solution is unclear, unfocused, and/or inconsistent.	There is no evidence of logical progression, and it is necessary.
Reviewers suggestions, comments, & score on level of agreement						

Appendix G: Final DNMC with question prompts

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?



\$48.30 /each

ECO FLO 1/4 HP
Submersible Utility
Pump

Model SUP55



\$98.12 /each

ECO FLO 1/3 HP
Submersible Utility
Pump

Model SUP56



Was ~~\$79.03~~
\$71.13 /each

Save \$7.90 (10%)

Superior Pump 1/2 HP
Submersible
Thermoplastic Utility
Pump

Model 91570



\$439.82 /each

Koshin 1 in. 1 HP
Centrifugal Pump with
Honda Engine

Model SEH-25L

Appendix H: Results of review of research on PS between 2000 and 2015 & List of reviewed papers

CODING DICTIONARY		
Variables	Values	Definitions
<u>Type of program</u>	1 through 3	1. 9-12
		2. 4-yr program
		3. Summer-camp or short experience.
<u>Student Preparation</u>	0, 1 and 2	0. None stated
		1. Advanced
		2. Normal
<u>Context</u>	0 through 4	0. None stated
		1. Tech ed. classes
		2. Engineering only
		3. Integrative STEM
		4. Science ed. - PBL
<u>Method - Type</u>	1 through 3	1. Qualitative
		2. Quantitative
		3. Mixed Methods
<u>Method - implementation</u>	1 through 3	1. Experimental
		2. Case study
		3. Review
<u>Outcome</u>	2 digit code – 11 through 16, 20, 30, 40	1. Achievement
		1. Self-efficacy
		2. Design skills
		3. Problem solving
		4. Spatial analysis
		5. GPA
		6. Mth-sci scores
		20. Retention, 30 Persistence, 40 Interest development

Papers	Type of program	Student Background	N = ?	Context	Method & Implementation	Outcomes
Atman, Kilgore & McKenna 2008	2	2	106	2	32	12
Bropy et al 2008	1	2		1	13	17
Docktor & Heller 2009	2	2	300	2	31	13
Elliott, et al , 20001	2	2	143	4	22	13
Eseryel, Ifenthaler & Ge 2013	1	3	159	3	31	13
Fantz et al - 2011	2	1	332	2	22	11
Gasiewski et al - 2012	2	2	73	3	32	40
Hirsch et al - 2005	1	2	391	0	21	11
Katsioloudis - 2014	2	2	35	3	21	14
Kilgore et al - 2007	2	2	124	2	31	12
Mendez et al - 2014	2	2	146	2	32	13
Ncube - 2006	1	2	176	2	22	15
Ortiz - 2015	3	2	30	3	31	16
Puente, Eijck & Jochems - 2014	2	2	240	2	32	12
Steif et al 2010	2	1	21	2	31	13
Taraban, Craig & Anderson - 2011	2	2	23	2	31	13
Wentz & Raebel - 2015	2	1	110	2	13	15
Zarske et al - 2014	1	1	80	3	32	40

List of papers reviewed

Atman, C. J., Kilgore, D. and McKenna A. (2008). Characterizing design learning: A mixed-methods study of engineering designers' use of language. *Journal of Engineering Education*, 97(3), 309-326.

Brophy, S., Klein, S., Portsmore, M., and Rogers, C. (2008). Advancing engineering education in P-12 classrooms. *Journal of Engineering Education*, 97(3), 369-387.

Docktor, J. and Heller, K. (2009). *Robust Assessment Instrument for Student Problem Solving*. Proceedings of the NARST 2009 Annual Meeting. Retrieved from http://groups.physics.umn.edu/physed/People/Docktor/research.htm#Research_Documents:

Elliott, B., Oty, K., Mcaerthur, J. & Clark, B. (2001). The effect of an interdisciplinary algebra/science course on students' problem solving skills, critical thinking skills and attitudes towards mathematics. *International Journal of Mathematical Education in Science and Technology*, 32(6), 811-816. DOI: 10.1080/00207390110053784.

Eseryel, D., Ifenthaler, D. & Ge. X. (2013). Validation Study of a method for assessing complex ill-structured problem solving by using causal representations. *Education Technology Research Development*, 61, 443-463. DOI 10.1007/s11423-013-9297-2

Fantz, T. D., Siller, T. J., and DeMiranda, M. A. (2011) Pre-Collegiate factors influencing the self-efficacy of engineering students. *Journal of Engineering Education*. 100 (3), 604-623.

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- Steif, P.S., Lobue, J. M., & Kara, L. B. (2010). Improving problem solving performance by inducing talk about salient problem features. *Journal of Engineering Education*, 99(2), 135-142.
- Taraban, R., Craig, C., and Anderson, E. E. (2011). Using paper-and-pencil solutions to assess problem solving skill. *Journal of Engineering Education*, 100(3), (498-519).
- Wells, J., Lammi, M., Gero, J., Grubbs, M., Parerri, M., and Williams, C. (2016). Characterizing design cognition of high school students: Initial analyses comparing those with and without pre-engineering experiences. *Journal of Technology Education*, 27(2), 78-91.
- Wentz, B., and Raebel, C. (2015). *Evaluation of high school pre-engineering curricula on freshman architectural engineering student performance*. In AEI 2015 Conference Proceedings - American Society of Civil Engineers, 495-499. Retrieved from Virginia Tech Libraries.
- Zarske, M. S., Gallipo, M. J., Yowell, J. L., and Reamon, D. T. (2014). *STEM high school: Does multiple years of high school engineering impact student choices and teacher instruction?* In Proceedings - 121st American Society of Engineering Education Annual Conference & Exposition, Indianapolis, IN (Paper ID #9254). Retrieved from Virginia Tech Libraries.

Appendix I: Instructor's solution to DNMC

SOLUTION: Design Challenge – Safe drinking water

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

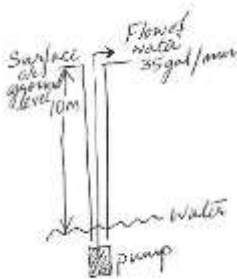
Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – HP) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and 1.0 HP = 746 W. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

We need a submersible pump to bring water from below ground in a well to ground level¹. The water is 10 meters below² ground. The rate of water flow needs to be 35 gallons per minute³. We need to purchase pump with enough power⁴ to do the job and it should be priced right⁵.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Need to show: 1) water level, 2) pump under water, 3) surface/ground level, 4) direction of flow of water

Power of pump – P (Variable for unknown)

Rate of water flow – 35 gal/min

Work done to lift the water – W (Variable for unknown)

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Power needed to bring water to the surface is a function of its change in Potential Energy or Work done per unit time. Δt is change in time or time elapsed.

Equation 1: $P = (W/\Delta t)$ | Equation 2: $W = F * d$ where d is distance traveled. | F is mass times gravity or Equation 3: $F = m g$

Therefore **Equation 4: $P = (mg*d) / \Delta t$** |

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

Conversion factors in blue. Unit conversions and Power calculation in brown

$$1 \text{ gal} = 3.78 \text{ L} \qquad \frac{35 \text{ gal}}{1 \text{ min}} * \frac{1 \text{ min}}{60 \text{ s}} * \frac{3.78 \text{ L}}{1 \text{ gal}} * \frac{1.0 \text{ kg}}{1 \text{ L}} = 2.208 \text{ kg/sec}$$

$$1 \text{ L has mass of 1kg} \qquad \frac{W}{\Delta t} = \frac{mg*d}{\Delta t} = \frac{(2.208 \text{ kg}) * 9.80 \text{ m/s}^2}{1 \text{ s}} * 10 \text{ m} = 216.4 \text{ Joules/s} = 216 \text{ Watts}$$

$$1 \text{ HP} = 746 \text{ Watts} \qquad \frac{216.4 \text{ Watts}}{1} * \frac{1 \text{ HP}}{746 \text{ Watts}} = .290 \text{ HP}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?


We need to purchase a pump with at least .290 HP which is approximately one-third HP. Assuming a reasonable efficiency of 60% gives about one-half HP.

I recommend Model 91570 which is a half HP submersible pump at \$71.13 to purchase.

It is also the cheapest one with enough power to do the task given above.

Appendix J: IRB & RCPS Approvals for Study, Recruitment email to scorers, Consent forms for scorers and students

MEMORANDUM

DATE: April 4, 2017 

TO: John Wells, Susheela S Shanta

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Engineering in 9-12: Investigation of Student Problem Solving Skills

IRB NUMBER: 17-377

Effective April 4, 2017, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the New Application request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at: <http://www.irb.vt.edu/pages/responsibilities.htm>

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Expedited, under 45 CFR 46.110 category(ies) 5,7**
Protocol Approval Date: **April 4, 2017**
Protocol Expiration Date: **April 3, 2018**
Continuing Review Due Date*: **March 20, 2018**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future



ROANOKE COUNTY PUBLIC SCHOOLS

Department of Instruction & Technology

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February 20, 2017

Ms. Susheela Shanta

Dr. John Wells, Associate Professor
Virginia Tech
Integrative STEM Education

Dear Ms. Shanta and Dr. Wells:

After a thorough review of your request to conduct research in Roanoke County Public Schools, the Research Review Committee has approved your research project entitled "Investigating and Understanding High School STEM Academy Student Problem Solving Skills" to be conducted with teachers and students in Roanoke County Public Schools during the second semester of this school year. Permission to conduct this research is conditional on you receiving approval from Virginia Tech's Institutional Review Board (IRB) and on full compliance with the conditions and affirmations specified in the Application for Approval to Conduct Research you submitted along with your documentation. Please forward to this office a copy of your research results once completed.

Best wishes for a successful research project. Please let us know if we can provide further assistance.

Sincerely,

Rhonda W. Stegall

Rhonda W. Stegall
Director of Secondary Instruction

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Research Study Description and Informed Consent Form

IRB Study 17-377

Title of Study: Engineering in 9-12: Investigation of Student Problem Solving Skills

Research Investigators:

Virginia Tech

John Wells, Associate Professor, Integrative STEM Education (540-231-8471/jgwells@vt.edu)

Susheela Shanta, PhD Candidate, Integrative STEM Education (540-632-5517/sshanta@vt.edu)

I. General Information Regarding Research Studies

A research study is an organized investigation designed to reveal new information about a problem or question. The research goal of this study is to use the information gained from this study to improve our understanding of a specific aspect of teaching and learning. Below you will find details specific to this study. As a participant in this study, your consent and permission are required. Participation within this study is voluntary, and you may refuse to participate, or may withdraw your consent at any time for any reason, without penalty. If you have any questions on this study at any time, please do not hesitate to contact the researchers name above.

II. Purpose of this Research

The purpose of this study is to better understand learning outcomes (problem-solving and critical thinking skills) of students that have been immersed in an instructional culture of using the content and practices of science and mathematics disciplines solve problems. In K-12 education integration of content and practices in the STEM fields provides opportunities for higher order learning because of higher cognitive demands in critical thinking and problem solving experiences. To conduct a study in this context, a problem statement (design-no-make challenge) will be provided to student participants and they will be asked to solve the presented problem and respond to the questions in the challenge. A scoring rubric will be used to score each response. These scores will be used to conduct the data analysis for the research study.

III. Procedures

Upon receipt of this completed consent form, your child will be verbally asked to confirm his/her agreement to participate in this study and also asked to sign the consent form (see the second page). During the class period, the teacher will provide the design-without-make brief to the entire class as a learning activity. The teacher will use all students' responses to work with the class to clarify any misconceptions and will review correct responses during a class period. Responses of the participants of this study, who have returned the consent form and confirmed their participation, will be copied while removing any identifying information from the response. The copies of your child's response will be used by the teacher/researcher (without your child's identifying information) for purposes of conducting this study.

IV. Risks

There are minimal to no known risks associated with participation in this study. However, there is always some possibility that previously unknown or uncommon risks be associated with your child's participation within this study. Therefore, you should report any concerns to the researcher.

V. Benefits

There are no tangible or intangible benefits to your child for his/her participation in this study. This in-class activity will benefit all students through the normal instructional approach taken by the teacher. This research will instead contribute to the body of new knowledge regarding student outcomes of critical thinking and problem solving skills and methods of measuring the same.

VI. Compensation

Students participating in this problem solving session will not receive compensation.

VII. Confidentiality

No identifying information of your child will be associated with his/her response. The researchers will receive the responses of the participants with no identifying information on the documents. The consent forms will be the only documents on which there will be student names and these will be maintained by the researcher separately in a secure location for the duration of the study. At no time will the researchers release the raw data to anyone other than the research team. However, because the IRB is responsible for the protection of human subjects involved in research, it is possible that they may view this study's collected data for auditing purposes.

VIII. Freedom to Withdraw

Participants are free to withdraw from the study at any time without penalty.

IX. Subject's Responsibilities

My child will voluntarily agree to participate in this study. As a participant he/she will have to provide a written design-no-make challenge response or solution to the teacher-researcher. This response will be copied without his/her name on the response, and this will be provided to the researchers thereby ensuring that his/her identity is not associated with the response provided to the researchers.

X. Subject's/Parent's/Guardian's Permission

I have read the consent form and the conditions of this project. I have had my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.

Student's Name

Parent/Guardian of Participant

Date

Email recruitment for Scorers

Hello _____!

Hope you are well.

I am working on my research study (Engineering in 9-12: Investigation of Student Problem Solving Skills) with the anticipation of completing my dissertation work this year. I will need help with scoring student responses to a design-no-make challenge which will contribute to the data collection for my study. I will explain the research questions and what I am trying to measure thoroughly if you agree to participate. Consent forms are attached and give you an idea of the time commitment.

At this time I am only asking if you may be available to help with reviewing the above mentioned? I expect it would take about 4 to 5 hours overall (within 8 to 10 days) to complete the tasks. There will be 2 scorers including you if you agree.

If you agree to participate, please sign the consent forms (you can type your name in for the signature, or you can use an electronic signature) and return via email to me. Once I receive your consent forms I will schedule our first meeting.

Thanks,

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants

in Research Projects Involving Human Subjects

Title of Project: Engineering in 9-12 grades: Investigation of student problem solving skills

IRB study 17-377

Investigator(s): Susheela Shanta, Researcher, sshanta@vt.edu, 540-632-5517

Dr. John Wells, jgwells@vt.edu, 540-231-8471

I. Purpose of this Research Project

The purpose of this study is to better understand learning outcomes of students that have been immersed in an instructional culture of using the content and practices of science and mathematics disciplines solve problems. In K-12 education integration of content and practices in the STEM fields provides opportunities for higher order learning because of higher cognitive demands in critical thinking and problem solving experiences. To conduct a study in this context, a design challenge (design-no-make challenge - DNMC) will be provided to student participants and they will be asked to solve the presented challenge/problem and respond to the questions in the challenge. A scoring rubric will be used to score each response. You are being asked to assist with the scoring of student responses.

II. Procedures

Upon receiving this consent form as your agreement to participate in this study, you will be asked to meet with the researcher to discuss the DNMC, the questions and the evaluation rubric. There will be two scorers involved and there will be a process of training for scoring that will require one hour of collaborative work to achieve consensus in scoring.

Your time commitment, which is expected to be four or five hours overall, is to assist in the following tasks:

1. Review the DNMC, the 5 questions asked in the DNMC, the instructor's response to the DNMC and the scoring rubric for the associated student response. Q&A with researcher;
2. Next, you will receive one student response to the DNMC, and you will be asked to score the response using the provided rubric. After completion, you will be asked to share your response with the other scorer and you will be asked to discuss the differences with the intention of arriving at a common understanding and score.
3. A second student response will be provided and the same process will be repeated. If your scores are within 2 points of each other, we will consider it sufficient and proceed to step 4. If that is not the case, then we will repeat with additional student responses until we achieve consensus in the first scoring attempt.
4. The student responses previously provided were not ones from the study participants. In this step you will be provided all the study participants student responses. There may be up to 11 responses. You will be asked to grade these independently at your convenience within a few days (to be agreed upon by you). Upon completion of grading, you will be asked to meet again to share your scores and seek to make any

final adjustments. These will then be turned over to the researcher and your task will be complete.

III. Risks

There are minimal to no risks associated with participation in this study. However, there is always some possibility that previously unknown or uncommon risks be associated with your personal participation within this study. Therefore, you should report any concerns to the researcher

IV. Benefits

There are no tangible or intangible benefits to you for your participation in this study. This research will instead contribute to the body of new knowledge regarding student outcomes of critical thinking and problem solving skills and methods of measuring the same.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

Your name and email address are the only identifying information associated with your participation in this pilot study. Only the researcher (Susheela Shanta) and the PI (Dr. John Wells) will have access to this information. Your electronic consent forms will be printed and maintained in a locked cabinet for the duration of this study. These will be destroyed after the completion of this study. Your emails will only be received by the researcher and will not be electronically shared with anyone else.

The returned DNMC and scored documents will also be maintained in a password protected computer. At no time will the researchers release identifiable results of the study to anyone other than individuals working on the project, without your written consent.

The Virginia Tech (VT) Institutional Review Board (IRB) may view the study's data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

There is no compensation for your participation in this study.

VII. Freedom to Withdraw

It is important for you to know that you are free to withdraw from this study at any time without penalty. You are free not to answer any questions that you choose or respond to what is being asked of you without penalty.

Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject.

Should you withdraw or otherwise discontinue participation, you will be compensated for the portion of the project completed in accordance with the Compensation section of this document.

VIII. Questions or Concerns

Should you have any questions about this study, you may contact one of the research investigators whose contact information is included at the beginning of this document.

Should you have any questions or concerns about the study's conduct or your rights as a research subject, or need to report a research-related injury or event, you may contact the VT IRB Chair, Dr. David M. Moore at moored@vt.edu or (540) 231-4991.

IX. Subject's Consent

I have read the Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

_____ Date _____

Subject signature (please type in your name)

Subject printed name

For questions or concerns about this research study, please contact Dr. John Wells (Virginia Tech) at 540-231-8471 or Ms. Susheela Shanta, (sshanta@rcs.k12.va.us), Teacher, RCPS at 540-632-5517.

Appendix K: Pilot Study Student Scores

PILOT STUDY SCORES						
<u>Participant</u>	<u>Useful Description</u>	<u>Sketch</u>	<u>Application of Physics</u>	<u>Application of Math</u>	<u>Logical Progression</u>	<u>Overall Success Score</u>
Student 1	3	2	2	1	0	8
Student 2	2	1	2	1	0	6
Student 3	3	2	3	3	3	14
Student 4	3	3	4	3	3	16
Student 5	3	3	4	3	3	16
Average Scores	2.2	1.8	2.6	2	1.8	12
<u>Percentage scores</u>	44%	36%	52%	40%	36%	48%

Appendix L: Student Responses to the DNMC – Main Study

Restated with Round 2 changes

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

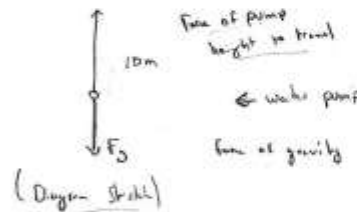
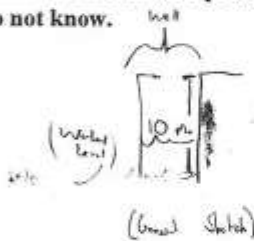
Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and 1.0 hp = 746 W. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

A volunteer team is trying to determine what horsepower a motor must be to pull water in a well. They have determined that using a motor is the most effective way & they have decided that 35 gal/min is the necessary rate that it must pump it.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

In order to determine the power of the water pump the relation between the 35 gal/min rate must be determined and the necessary power to get the water to the top of the well must be determined. In determining the ~~power~~ power of the pump, the force on the water must be found using Force = Force of gravity times distance. This value labeled 'x' must then be multiplied by the rate of 35 gal/min to determine the power. Once this is completed, a new value 'x_n' needs to be converted to hp.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$F = dVg r$$

$$F = 10 \text{ m} \left(9.8 \frac{\text{m}}{\text{s}^2} \right) \left(350 \frac{\text{m}^3}{\text{min}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)$$

$$F = 57.167 \text{ gal} \cdot \text{m}^3/\text{s}$$

Then convert to Watts. $W = 156.66$

Then convert to hp. $\text{hp} = .21$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

Need a $\frac{1}{4}$ hp motor.

I would pick motor 1 for \$48.30.

Restated with Round 2 changes

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

$$p = \frac{w}{t} \quad f = m \cdot a$$

$$w = f \cdot d$$

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35 gal/min. Remember, in America we sell electric motors in horsepower, not watts, and 1.0 hp = 746 W. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences. Essentially, need to determine the most effective, (both performance wise and economically), pump to be used. Pump has to be able to move 35 gal of water 10 meters upwards in 1 minute. Additionally, power needs to be in hp for American units/products.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

power = work ÷ time
 work = force · distance
 force = mass · acceleration
 acceleration = $\frac{\text{distance}}{\text{time}^2}$

$$\frac{35 \text{ gal}}{1 \text{ min}} = \frac{\text{volume}}{\text{time}} \quad t = 60 \text{ seconds}$$

7.) Divide resulting Power (Watts) by 746 W to find needed hp

- 1.) Solve for acceleration.
- 2.) Find mass of 35 gallons of water (1 liter = 1 kg I think?) (35 gal ≈ 133 L)
- 3.) Multiply m · a to find force
- 4.) Add 9.8 · 133 to original ma (cause it has to overcome gravity)
- 5.) Multiply resulting force by distance (10 m)
- 6.) Divide resulting work by 60 seconds

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$\text{acceleration} = \frac{1}{300} \text{ m/s}^2$$

$$f = \frac{1}{360} \cdot 133 = 0.369 \frac{\text{kgm}}{\text{s}^2} + 9.8 \cdot 133 = 1,303.77$$

$$W = 1,303.77 \cdot 10 = 13,037.7$$

$$P = \frac{13,037.7}{60} = 217.295 \text{ Watts}$$

$$P = \frac{217.295 \text{ W}}{1} \cdot \frac{1 \text{ hp}}{746 \text{ W}}$$

$$= 0.29128 \text{ hp}$$

$$\frac{1}{4} = .25$$

$$\frac{1}{3} = 0.333$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

$$\frac{1}{4} \text{ hp} \approx .25 \text{ hp}$$

$$\frac{1}{3} \text{ hp} = .33 \text{ hp}$$

$$\frac{1}{2} \text{ hp} = .5 \text{ hp}$$

$$1 \text{ hp} = 1 \text{ hp}$$

0.29128 hp
between these
two, need minimum
 $\frac{1}{3}$ hp

In order to pump 35 gal/min, 0.29128 hp is required. This is between $\frac{1}{4}$ hp + $\frac{1}{3}$ hp, meaning we will have to "size up" to meet the min. requirement. Therefore, only $\frac{1}{3}$ hp, $\frac{1}{2}$ hp, + 1hp are options. I would recommend purchasing the $\frac{1}{2}$ hp pump. I recommend this not because of hp (because obviously $\frac{1}{3}$ hp is closer to needed power), but because of price. The $\frac{1}{2}$ hp pump costs \$71.13 + has a 3-yr limited warranty + it is a certified product. The $\frac{1}{3}$ hp costs \$98.12 with only a 1-yr warranty + isn't certified. Therefore, the $\frac{1}{2}$ hp motor is the best option due to it having enough hp to push 35 gal/min + it being the most cost-efficient option.

Restated with Round 2 changes**Description of Scenario**

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

The problem above describes a dilemma that is being experienced in a third world country. The issue of safe drinking water is what a volunteer team is attempting to solve. In order to avoid standard bucket using methods that may not seem sanitary, they are considering an electric pump. The problem asks that water should be gathered at 35 gal/min, for the right price.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Some equations that could be used are conversion rates for volume and time, in addition to the equation for power, work, energy, force, and possibly torque. Some fluid mechanics laws would also be utilized when referring to the motion of the water as it travels from the pump up to the surface. In order to determine the power of the pump necessary, you must find how much force it takes to move water vertically 10 meters and then find out how much power is necessary to attain the necessary speed.

Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$F = mg$$

$$F = mgh$$

$$F = \text{mass of } 1g \cdot 9.8 \cdot 10$$

$$F = 98 \text{ (mass of 1 gal)}$$

$$F = 98x$$

$$P = F \cdot d \cdot f_{\text{rate}}$$

$$P = 98x \cdot d \cdot 35 \text{ gal/min}$$

$$P = 773 \text{ W}$$

$$\frac{1 \text{ hp}}{746} = \frac{x}{773} \quad x = 1.03 \text{ hp needed}$$

2 of opt 3.

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

The best choice is to buy motor 3, but purchase two so that you can attain the speed necessary.

\$142.26

Restated with Round 2 changes**Description of Scenario**

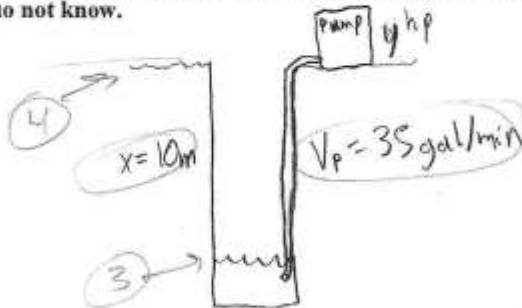
A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences. I am challenged to design an electric pump so villagers in a third world country can potentially use it to get water from a well. The target pump rate I have to achieve is 35 gallons/minute and have to do this through picking the right motor with a certain horsepower.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Since the water is down 10 meters, it is impossible for the water to rise without a force greater than the force of gravity pulling it down. However, I'm not too sure on what equation I have to use. If I had to take

a wild guess, I think the equation to find the hp needed would be $y = \frac{x(V_p)}{746}$ where 746 accounts for the number of watts in a horsepower

Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$P = \frac{X(V_p)}{746} = \frac{10m(35gal/min)}{746} = .469 \text{ hp}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

I think the best pump to pick would be the one with a $\frac{1}{2}$ hp motor. Even though my calculation was less buying the one w/ $\frac{1}{3}$ hp would not create enough force to counter gravity and reach the pump target velocity. Total cost would be \$71.13 for just the pump and based on what I know, the 10m tubing would cost around \$5.

Now that I think about it, I think the tube diameter is something that would be a part of the equation.

Restated with Round 2 changes

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

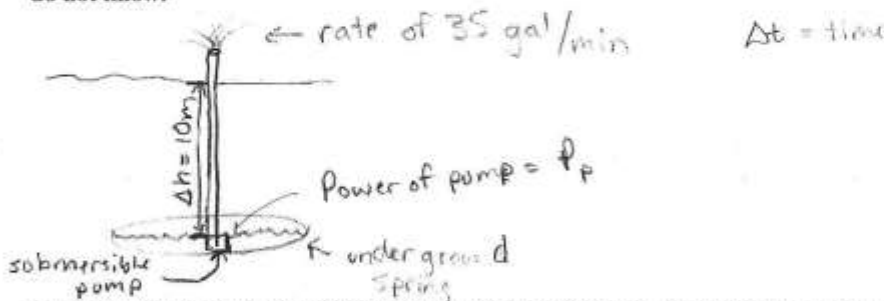
Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and 1.0 hp = 746 W. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

The problem stated above involves designing a pump for the specific underground spring 10 meters below at a rate of 35 gallons/minute.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

In order to determine the power of the water pump, you would need to know the physics of work and power.

Work = Force x distance

Power = $\frac{\text{Work}}{\text{time}}$

Power = $\frac{\text{Force} \times \text{distance}}{\text{time}}$

Force = mass x acceleration

acceleration = $\frac{\text{velocity}_2 - \text{velocity}_1}{\Delta t}$

Density = $\frac{\text{mass}}{\text{volume}}$

Density of water = 1 g/cm³

My strategy is to use the given rate as the velocity of the water and combine that with knowledge of the density of water to use in the power equation derived above.

3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

For ease of calculation, all units will be in metric until power is determined, the the conversion will be made to horse power $\Delta t = 60 \text{ seconds}$

$$V = \frac{35 \text{ gal} \cdot 3.785 \text{ cm}^3}{60 \text{ sec} \cdot 1 \text{ gal}} = 2,207.9 \text{ cm}^3/\text{sec}$$

$$a = \frac{2,207.9 \text{ cm}^3/\text{sec}}{60 \text{ sec}} = 36.798 \text{ cm}^3/\text{sec}$$

$$D = \frac{m}{V}, 3,785 \text{ cm}^3 (1 \text{ g/cm}^3) = m$$

$$3.785 \text{ kg} = 3,785 \text{ g} = m$$

$$P_p = \frac{(m a) \times \Delta h}{\Delta t}$$

$$P_p = \frac{(3.785 \text{ kg})(36.798 \text{ cm}^3/\text{sec})(100 \text{ cm})}{60 \text{ sec}}$$

$$P_p = 232 \text{ Watts}$$

$$P_p = \frac{232 \text{ Watts}}{1} \times \frac{1 \text{ hp}}{746 \text{ W}} = .3109 \text{ hp}$$

Q4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

The power of the motor I need is around .3109 hp.

This would mean that the $\frac{1}{3}$ hp motor would be sufficient, it will cost \$92.12 for 1 unit.

Restated with Round 2 changes

Description of Scenario

A small village in a third world country has determined that its most pressing need is for safe drinking water. A volunteer team determined the location of an appropriate underground spring and dug the well. The well is 10.0 meters deep and one way to access the water in the well, would be to lower buckets into the well. The concerns with using buckets to retrieve the water are, that the buckets will become dirty over time and defeat the purpose of the safe drinking water, and, using buckets would be time consuming, difficult, and create hardship for those who need the water. The volunteer team decided to use an electric submersible pump to bring the water safely and cleanly to the surface for storage and use.

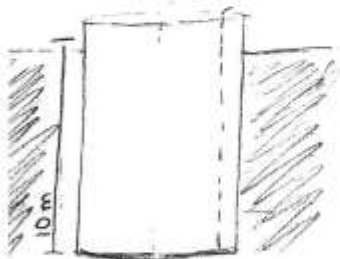
Challenge

Your task in this challenge, is to design a suitably sized (power – measured in horsepower – hp) and priced (dollars) submersible pump to supply water at a rate of 35gal/min. Remember, in America we sell electric motors in horsepower, not watts, and $1.0 \text{ hp} = 746 \text{ W}$. For pricing, use the information provided in the attachment.

Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

The volunteer team is deciding to create an electric pump to obtain clean drinking water from the well. The electric pump needs to be of the correct dimensions and have a suitable price.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you not know.



Length of pipes = $l = 10\text{m}$

$$W = Fd = (x \text{ hp})(10\text{m})$$

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

To determine the power of the water pump, I used the equation $\text{work} = \text{force} \times \text{distance}$
 $W = Fd$

to solve for the force.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

U

$$W = 35 \text{ gal/min} \times 10 \text{ m}$$

1.5 m
1.5 m

$$W = 35 \text{ gal/min} \times 10 \text{ m} \\ = 350 \text{ W}$$

$$\frac{350 \text{ W}}{746 \text{ W}} \times 1 \text{ hp} = .47 \text{ hp}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

Based on the work, the pump has to be at least .5 hp. Anything less will not work, while anything more would be too much force and would be too expensive.

The 1/2 hp pump would cost \$71.13.

I

Restated with Round 2 changes**Description of Scenario**

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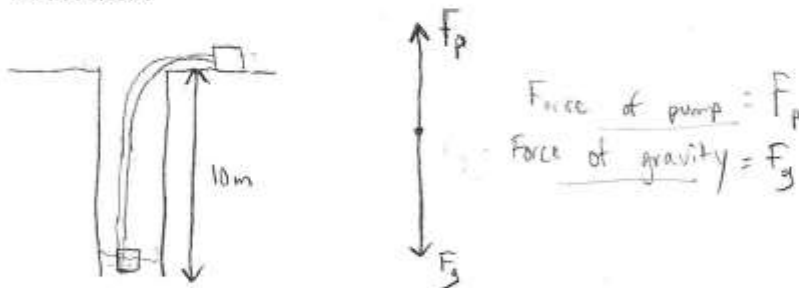
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Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

There must be enough power (or horsepower) is the motor to pump the water out of the well. It must pump out at a certain rate of 35 gal/min. The well is 10.0 m deep.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

To determine the power in the pump, equations for work and power itself, $W (\text{work}) = F (\text{force}) * \text{Distance}$ or ΔE (change in energy), ΔE would best work, $(\frac{1}{2}mv^2 + mgh, = \frac{1}{2}Kx^2 + mgh$

You would then use $\frac{W}{t}$ ($\frac{\text{work}}{\text{time}}$) to find power.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$\frac{1}{2} m v_1^2 + m g h_1 = \frac{1}{2} m v_2^2 + m g h_2 \quad \text{(Energy is 0 before pumping.)}$$

$$0 + 0 = \frac{1}{2} (35 \text{ gal/min})^2 + (10 \text{ m/s}^2)(10)$$

$$W = 712 \text{ J} \quad P = \frac{712 \text{ J}}{1 \text{ min}} = 712 \text{ W} = \boxed{.95 \text{ hp}}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

Based on the calculations, you would need the 1 hp pump. It costs \$439.82.

Restated with Round 2 changes

Description of Scenario

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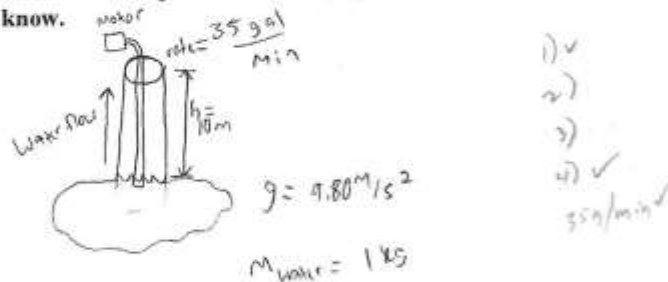
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Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

I must calculate the power needed to lift the water from the well to ground level. Then I need to generate a price for the electric motor.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

Power = $\frac{\text{Work}}{\text{Time}}$ ✓, so I would first need to calculate work by

using work = mass(gravity)(height), then I can find the time by taking

the inverse of the given rate (35 gal/min). Power may then be calculated.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$\text{Work} = \text{mass}(\text{gravity})(\text{height})$$

$$\text{work} = (1 \text{ kg})(9.80 \text{ m/s}^2)(10.0 \text{ m})$$

$$\text{Work} = 98.0 \text{ J}$$

$$\text{Time} = \frac{1}{35 \text{ g/min}}$$

$$\text{Time} = .0286 \text{ min} \times \frac{60 \text{ s}}{1 \text{ min}}$$

$$\text{Power} = \frac{\text{work}}{\text{time}} = \frac{98.0 \text{ Nm}}{1.72 \text{ s}}$$

$$\text{time} = 1.72 \text{ s}$$

$$\text{Power} = 57.0 \text{ W}$$

$$\text{Power} = 57.0 \text{ W} \cdot \frac{1.0 \text{ hp}}{746 \text{ W}} = .0764 \text{ hp}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

I would pick the ECO FLO 1/4 HP Submersible Utility Pump for \$48.30. This would have plenty of horsepower to get the job done and it is also very affordable.

Restated with Round 2 changes**Description of Scenario**

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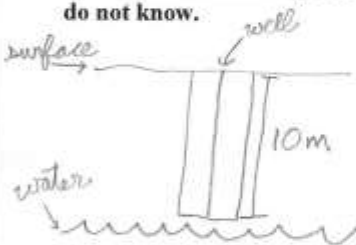
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Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

In a third world country there is a need for safe drinking water. A volunteer team found a spring and is going to make a 10m deep well. Using buckets defeats the purpose of safe drinking water therefore they will install a pump. What horsepower + price?

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



rate of 35 gallons/minute
pump: price = ?
horsepower = ?

Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

To determine the power of the water pump you will use the information that was given to you and then plug it into an equation

- depth of the well is 10 meters
 - the rate of water leaving the well must be 35 gal/min
 - after getting the answer you must convert watts to horsepower
- $740 \text{ watts} = 1 \text{ horsepower}$
power = distance * rate

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$\begin{aligned} \Rightarrow \text{power} &= \text{distance} * \text{rate} \\ \text{power} &= 10\text{m} * 35 \text{ gal/min} \\ \text{power} &= 350 \text{ watts} \\ &= \frac{350 \text{ watts}}{1} * \frac{1 \text{ horsepower}}{740 \text{ watts}} \\ &= 0.473 \text{ horsepower} \end{aligned}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

according to the calculations the well will need at least a 0.473 horsepower motor. A motor is not sold exactly in this size which means we must size up. The next greatest motor size is of

\Rightarrow 0.5 horsepower. The price of this is \$71.13

Superior Pump 1/2 HP
Submersible Thermoplastic
Utility Pump = \$71.13

Restated with Round 2 changes

Description of Scenario

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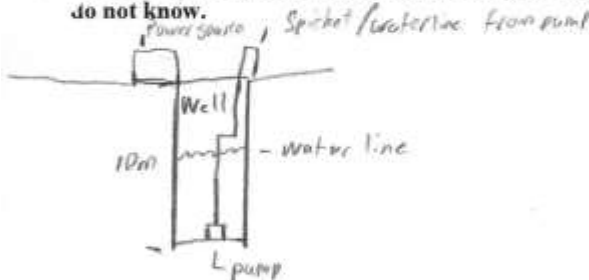
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Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

I see that the team has decided that a pump is a desirable the best choice, and that their power rating is correct. Price is also an issue. The pump must bring 35 gallons up 10m every minute.

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

$Work = Force \cdot distance$
 $Power = \frac{Work}{Time}$

1) define the work. Work can be related to change in energy. $Peg = mgh$
 (potential (gravitational) energy = mass \cdot g \cdot height)

$Work = 35 \text{ gallons} \cdot 10 \frac{m}{s^2} = 19m$
 (in kilograms)

2) divide by 60 (seconds / minute) 3) convert Force w to hp.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$\Delta P_{eq} = \rho g A h \quad \Delta h = 10 \text{ m} \quad 1 \text{ pint of water} = 1 \text{ pound of water}$$

$$\Delta P_{os} = (127)(10)(10) \quad g = 10 \text{ m/s}^2 \quad 35 \text{ gallons} = 280 \text{ pints} = 280 \text{ pounds}$$

$$\Delta P_{eq} = 12700 \text{ J} \quad m = 127 \text{ kg} \quad 280 \text{ lbs} = 127 \text{ kg}$$

$$\Delta t = 60 \text{ seconds}$$

$$\text{Power} = \frac{\Delta P_{eq}}{\Delta t} = \frac{12700}{60} = 211.7 \text{ W} = .284 \text{ Hp}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

We will need greater than a $\frac{1}{4}$ Hp pump. A $\frac{1}{3}$ Hp pumps available, but the $\frac{1}{2}$ Hp pump has more value for money.

	$\frac{1}{3}$ Hp	$\frac{1}{2}$ Hp
Price	\$98.12	\$71.13
Warranty	12 month	36 month limited

The $\frac{1}{2}$ Hp is better in every category, and would be more reliable for running at less than max power to meet needs.

Cost = \$71.13, Free shipping

Restated with Round 2 changes**Description of Scenario**

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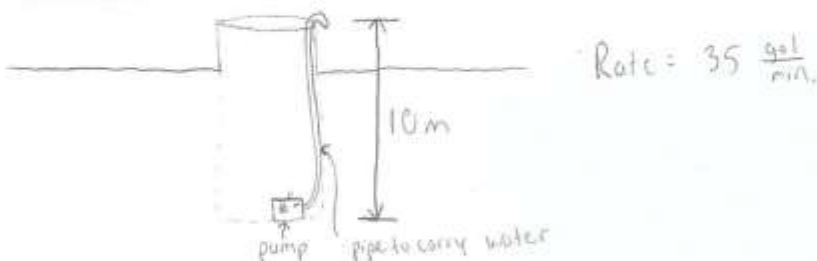
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Q 1a) What is your understanding of the challenge described above? Describe using your own words in a few sentences.

There is a small village that doesn't have safe drinking water, and using buckets isn't a viable solution, so my task is to design a pump with an efficient power and price to bring the water

Q 1b) Based on what you wrote above, draw a sketch to describe the scenario, and label the sketch to

show the information provided above (e. g. the depth of the well is 10 meters). Use variables for what you do not know.



Q 2) How could you determine the power of the water pump? State any laws and equations you would use and explain your strategy in a few sentences.

The power is the amount of horsepower the pump has that will be used to get the water out of the well. The formula $P = \text{Rate} \cdot d$ will be used to

determine the wattage of the pump and then we multiply this by $\left(\frac{1 \text{ hp}}{746 \text{ W}}\right)$ to find the amount of hp it will need.

Q 3) Based on your response to question 2 go through the process you have outlined, and show your calculations to determine the power of the pump (in horsepower).

$$P = \text{Rate} \cdot d = 35 \frac{\text{gal}}{\text{min.}} (10 \text{ m}) = 350 \text{ W} \left(\frac{1 \text{ hp}}{746 \text{ W}} \right) = 0.47 \text{ hp}$$

Q 4) Based on your work in question 3, what is the power of the motor you need? Using the motor pricing information provided, which motor would you pick and how much will it cost?

The power of the motor we will need is $\frac{1}{2}$ or 0.5 hp.
We will pick the 3rd motor in the list which is a $\frac{1}{2}$ hp motor and is priced at \$71.13.

