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A conceptual framework for integrated STEM education

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Abstract

The global urgency to improve STEM education may be driven by environmental and social impacts of the twenty-first century which in turn jeopardizes global security and economic stability. The complexity of these global factors reach beyond just helping students achieve high scores in math and science assessments. Friedman (The world is flat: A brief history of the twenty-first century, 2005) helped illustrate the complexity of a global society, and educators must help students prepare for this global shift. In response to these challenges, the USA experienced massive STEM educational reforms in the last two decades. In practice, STEM educators lack cohesive understanding of STEM education. Therefore, they could benefit from a STEM education conceptual framework. The process of integrating science, technology, engineering, and mathematics in authentic contexts can be as complex as the global challenges that demand a new generation of STEM experts. Educational researchers indicate that teachers struggle to make connections across the STEM disciplines. Consequently, students are often disinterested in science and math when they learn in an isolated and disjoined manner missing connections to crosscutting concepts and real-world applications. The following paper will operationalize STEM education key concepts and blend learning theories to build an integrated STEM education framework to assist in further researching integrated STEM education.

Keywords: Integrated STEM, Framework, STEM pedagogies, Scientific inquiry, Engineering design

Background

Many global challenges including "climate change, overpopulation, resource management, agricultural production, health, biodiversity, and declining energy and water sources" need an international approach supported by further development in science and technology to adequately address these challenges (Thomas and Watters 2015, p. 42). Yet numerous educational research studies have indicated that students' interest and motivation toward STEM learning has declined especially in western countries and more prosperous Asian nations (Thomas and Watters). Concern for improving STEM education in many nations continues to grow as demand for STEM skills to meet economic challenges increasingly becomes acute (English 2016; Marginson et al. 2013; NAE and NRC 2014). Driven by genuine or perceived current and future shortages in the STEM workforce, many education systems and policy makers around the globe are preoccupied with advancing competencies in STEM domains. However, the views on the nature and development of proficiencies in STEM education are diverse, and increased focus on integration raises new concerns and needs for further research (English 2016; Marginson et al. 2013).

Although the idea of STEM education has been contemplated since the 1990s in the USA, few teachers seemed to know how to operationalize STEM education several decades later. Americans realized the country may fall behind in the global economy and began to heavily focus on STEM education and careers (Friedman 2005). STEM funding for research and education then increased significantly in the USA (Sanders 2009). The urgency to improve achievement in American Science, Technology, Engineering and Mathematics education is evident by the massive educational reforms that have occurred in the last two decades within these STEM education disciplines (AAAS 1989, 1993; ABET 2004; ITEA 1996, 2000, 2002, 2007; NCTM 1989, 2000; NRC 1989, 1994, 1996, 2012). Although these various documents seek to leverage best practices in education informed by research on how people learn (NRC 2000a, 2000b),

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competing theories and agendas may have added confusion to the complexity of integrating STEM subjects. Recent reforms such as *Next Generation Science Standards* (NGSS) (NGSS Lead States 2013) and *Common Core State Standards for Mathematics* (CCSSM) (National Governors Association Center for Best Practices & Council of Chief State School Officers 2010) advocate for purposefully integrating STEM by providing deeper connections among the STEM domains. One of the most recent NAE and NRC (2014) documents, *STEM Integration in K-12 Education*: *Status*, *Prospects*, *and an Agenda for Research*, recognize problems with competing agendas, lack of coherent effort, and locating and teaching intersections for STEM integration. The *Committee on Integrated STEM Education* was charged to assist STEM education stakeholders by (a) carefully identifying and characterizing existing approaches to integrated STEM education, (b) review evidence of impact on student learning, and (c) help determine priorities for research on integrated STEM education. This report was created as a way to move STEM educators forward by creating a common language of STEM integration for research and practice. This effort indicates that further work remains to improve STEM integration in practice and establishes a need to conduct more research on integrated STEM education (NAE and NRC 2014).

One outcome of improving achievement in STEM education in many countries is preparing a workforce that will improve national economies and sustain leadership within the constantly shifting and expanding globalized economy. Wang, Moore, Roehrig, and Park (2011) stated that:

> Growing concern about developing America's future scientists, technologists, engineers, and mathematicians to remain viable and competitive in the global economy has re-energized attention to STEM education. To remain competitive in a growing global economy, it is imperative that we raise student's achievement in STEM subjects. (p. 1)

European STEM educators and industrialists have identified a widening STEM skills gap among the workforce. Improving STEM education is driven increasingly by economic concerns in developing and emerging countries as well (Kennedy and Odell 2014). While STEM student enrollment and motivation has declined in many western countries, various studies have shown an increased interest among young people in developing nations such as India and Malaysia (Thomas and Watters 2015).

Seeking coherency in STEM education

Much ambiguity still surrounds STEM education and how it is most effectively implemented (Breiner et al. 2012). STEM education is often used to imply something innovative and exciting yet it may, in reality, remain disconnected subjects (Abell and Lederman 2007; Sanders 2009; Wang et al. 2011). However, an integrated curricular approach could be applied to solve global challenges of the modern world concerning energy, health, and the environment (Bybee 2010; President's Council of Advisors on Science and Technology (PCAST) 2010). Kennedy and Odell (2014) noted that the current state of STEM education:

> has evolved into a meta-discipline, an integrated effort that removes the traditional barriers between these subjects, and instead focuses on innovation and the applied process of designing solution to complex contextual problems using current tools and technologies. Engaging students in high quality STEM education requires programs to include rigorous curriculum, instruction, and assessment, integrate technology and engineering into the science and mathematics curriculum, and also promotes scientific inquiry and the engineering design process. (p. 246)

STEM education can link scientific inquiry, by formulating questions answered through investigation to inform the student before they engage in the engineering design process to solve problems (Kennedy et al. 2014). Quality STEM education could sustain or increase the STEM pipeline of individuals preparing for careers in these fields (Stohlmann et al. 2012). Improving STEM education may also increase the literacy of all people across the population in technological and scientific areas (NAE and NRC 2009; NRC 2011).

As the USA and other countries work to build their capacity in STEM education, they will need to interact with each other in order to enhance their efforts in international scientific engagement and capacity building to provide quality education to all of their students (Clark 2014, p. 6).

Defining integrated STEM education

Over the last few decades, STEM education was focused on improving science and mathematics as isolated disciplines (Breiner et al. 2012; Sanders 2009; Wang et al. 2011) with little integration and attention given to technology or engineering (Bybee 2010; Hoachlander and Yanofsky 2011). Furthermore, STEM subjects often are taught disconnected from the arts, creativity, and design (Hoachlander and Yanofsky 2011). Sanders (2009) described integrated STEM education as "approaches that explore teaching and learning between/among any two or more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects" (p. 21). Sanders suggests that outcomes for learning at least one of the other STEM subjects should be purposely designed in a course—such as a math or science learning outcome in a technology or engineering class (Sanders 2009). Moore et al. (2014) defined integrated STEM education as "an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems" (p. 38). Integrated STEM curriculum models can contain STEM content learning objectives primarily focused on one subject, but contexts can come from other STEM subjects (Moore et al.). We, however, define integrated STEM education as the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning.

The authors acknowledge that there are limits to this approach to teaching integrated STEM education. Some might view this approach too focused on career pathways with emphasis on STEM practices and authentic application of STEM knowledge. The authors acknowledge that teaching STEM from the proposed approach is not possible in all circumstances and could limit the content taught from this approach. Some necessary knowledge in mathematics and sciences that are theoretically focused may not provide authentic engineering design applications as well as common STEM practices limited by current technology.

Limits of current integrated practices

Making crosscutting STEM connections is complex and requires that teachers teach STEM content in deliberate ways so that students understand how STEM knowledge is applied to real-world problems. Currently, crosscutting connections remain implicit or can be missing all together (NAE and NRC 2009). The *Committee on Integrated STEM Education* noted that:

> Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines. Also, students do not always or naturally use their disciplinary knowledge in integrated contexts. Students will thus need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context, to connect those ideas productively, and to reorganize their own ideas in ways that come to reflect normative, scientific ideas and practices. (NAE and NRC 2014, p. 5)

Increased integration of STEM subjects may not be more effective if there is not a strategic approach to implementation. However, well-integrated instruction provides opportunities for students to learn in more relevant and stimulating experiences, encourages the use of higher level critical thinking skills, improves problem solving skills, and increases retention (Stohlmann et al. 2012). Building a strategic approach to integrating STEM concepts requires strong conceptual and foundational understanding of how students learn and apply STEM content. The following theoretical framework for integrated STEM seeks to propose such an approach.

Conceptual framework for integrated STEM education

Research in integrated STEM can inform STEM education stakeholders to identify barriers as well as determine best practices. A conceptual framework is helpful to build a research agenda that will in turn inform STEM stakeholders to realize the full potential of integrated STEM education. We propose a conceptual framework around learning theories and pedagogies that will lead to achieving key learning outcomes. Developing a conceptual framework for STEM education requires a deep understanding of the complexities surrounding how people learn, specifically teaching and learning STEM content. Research shows STEM education teaching is enhanced when the teacher has sufficient content knowledge and domain pedagogical content knowledge (Nadelson et al. 2012). Instead of teaching content and skills and hoping students will see the connections to real-life application, an integrated approach seeks to locate connections between STEM subjects and provide a relevant context for learning the content. Educators should remain true to the nature in which science, technology, engineering, and mathematics are applied to real-world situations. *The Next Generation Science Standards* (NRC 2012) suggest closer study of practices may help to provide a framework for integrating STEM subjects.

The proposed framework as presented is intended for secondary education, specifically high school level educators and learners. The following graphic (Fig. 1) helps capture a conceptual framework for integrated STEM education and will also serve as a frame for the core concept of the paper. We will reference the graphic throughout the paper to further explain key concepts and make connections across STEM practices. The aim of this paper is to propose a conceptual framework to guide STEM educators and to build a research agenda for integrated STEM education.

Figure 1 illustrates the proposed conceptual framework for integrated STEM education. The image presents a block and tackle of four pulleys to lift a load, in this case "situated STEM learning." Block and tackle is a pulley system that helps generate mechanical advantage to lift loads easier. The illustration connects situated learning, engineering design, scientific inquiry, technological literacy, and mathematical thinking as an integrated system. Each

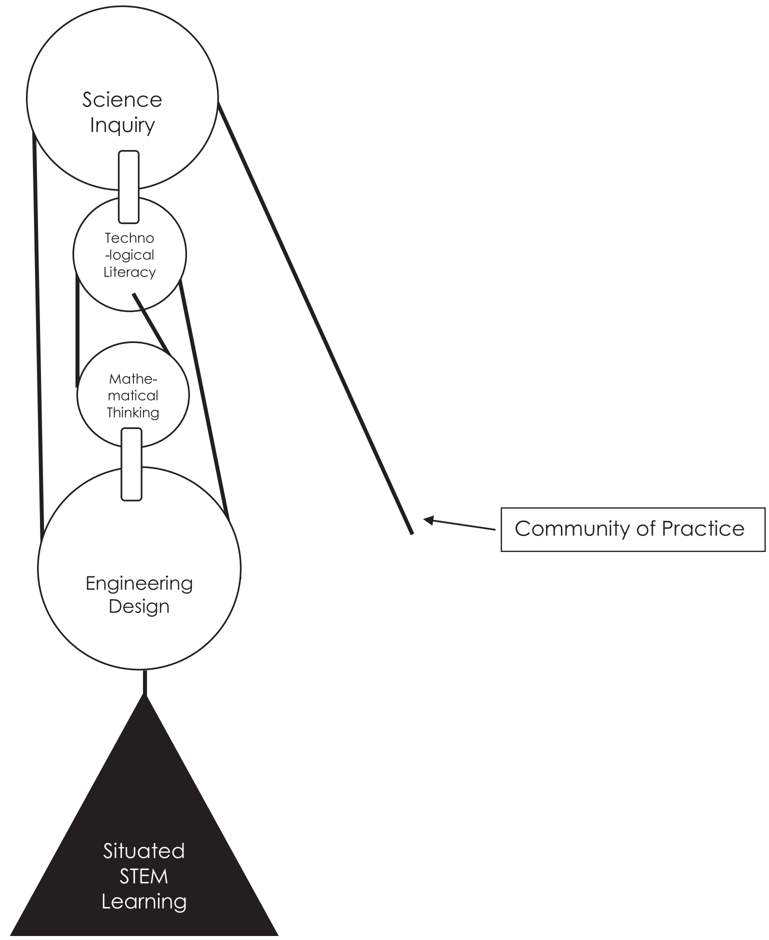

Fig. 1 Graphic of conceptual framework for STEM learning

pulley in the system connects common practices within the four STEM disciplines and are bound by the rope of community of practice. A complex relationship of the pulley system must work in harmony to ensure the integrity of the entire system. The authors are not suggesting that all four domains of integrated STEM must occur during every STEM learning experience but STEM educators should have a strong understanding of the relationship that can be established across domains and by engaging a community of practice. Like any mental model, there are limits to looking at integrated STEM education using this approach. We will seek to provide support for this mental model while acknowledging the limits in viewing STEM education this way. Each part of the conceptual framework will be described in detail. We encourage readers to refer back to Fig. 1 to help better understand the various aspects of this proposed framework.

Situated STEM learning

The authors would advocate most content in STEM can be grounded within the *situated cognition theory* (Brown et al. 1989; Lave and Wenger 1991; Putnam and Borko 2000). Foundational to this theory is the concept that understanding how knowledge and skills can be applied is as important as learning the knowledge and skills itself. Situated cognition theory recognizes that the contexts, both physical and social elements of a learning activity, are critical to the learning process. When a student develops a knowledge and skill base around an activity, the context of that activity is essential to the learning process (Putnam and Borko 2000). Often when learning is grounded within a situated context, learning is authentic and relevant, therefore representative of an experience found in actual STEM practice. When considering integrating STEM content, engineering design can become the situated context and the platform for STEM learning.

Certainly, there is some STEM content that cannot be situated in authentic contexts, therefore limiting this model to only content that can be applied through situated learning approaches. Within Fig. 1, the analogy of situated learning as a “load” to lift may present a limited perspective of this educational model.

Pulley #1: engineering design

Engineering design can provide the ideal STEM content integrator (NAE and NRC 2009; NRC 2012). Moreover, an engineering design approach to delivering STEM education creates an ideal entry point to include engineering practices into existing secondary curriculum. Using engineering design as a catalyst to STEM learning is vital to bring all four STEM disciplines on an equal platform. The very nature of engineering design provides students with a systematic approach to solving problems that often occur naturally in all of the STEM fields. Engineering design provides the opportunity to locate the intersections and build connections among the STEM disciplines, which has been identified as key to subject integration (Frykholm and Glasson 2005; Barnett and Hodson 2001).

Science education can be enhanced by infusing an engineering design approach because it creates opportunity to apply science knowledge and inquiry as well as provides an authentic context for learning mathematical reasoning for informed decisions during the design process. The *Conceptual Frameworks for New Science Education Standards* (NRC 2012) in the USA recommend that students are given opportunities to design and develop science investigations and engineering design projects across all K-12 grade levels (p. 9). The analytical element of the engineering design process allows students to use mathematics and science inquiry to create and conduct experiments that will inform the learner about the function and performance of potential design solutions before a final prototype is constructed. This approach to engineering design allows students to build upon their own experiences and provide opportunities to construct new science and math knowledge through design analysis and scientific investigation. According to Brown et al. (1989), these are necessary experiences for effective learning:

> Engineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science—and, for many, their interest in science—as they recognize the interplay among science, engineering, and technology. We are convinced that the engagement in the practices of engineering design is as much a part of learning science as engagement in the practices of science. (p.12)

In engineering practice, engineering design and scientific inquiry are interwoven through an intricate process of design behaviors and scientific reasoning (Purzer et al. 2015). Though there is a notable difference between engineering design and scientific inquiry, two central ways they converge according to Purzer et al. (2015) are "(a) reasoning processes such as analogical reasoning as navigational devices to bridge the gap between problem and solution and (b) uncertainty as a starting condition that demands expenditure of cognitive resources…" (p. 2). Additionally, both engineering design and scientific inquiry accentuate learning by doing (Purzer et al. 2015). Similar to situated learning theory, approaching all STEM content through engineering design is not always possible. For example, some science content is currently theoretically based and cannot be taught by design-based instruction.

Pulley #2: scientific inquiry

Learning science in a relevant context and being able to transfer scientific knowledge to authentic situations is key to genuine understanding. An inquiry approach to instruction requires teachers to "encourage and model the skills of scientific inquiry, as well as the curiosity, openness to new ideas, and skepticism that characterize science" (National Research Council 1996, p. 37). Scientific inquiry prepares students to think and act like real scientists, ask questions, hypothesize, and conduct investigations using standard science practices. However, an inquiry-based approach involves a high level of knowledge and engagement on the part of the teachers and students. Teachers often feel unprepared because they are lacking authentic scientific research and inquiry experiences themselves (Nadelson et al. 2012). They harbor misconceptions about hands-on instruction, viewing a series of tasks and lab activities as being equivalent to scientific inquiry. However, practical and procedurally based hands-on activities are not equivalent to true science inquiry but must include "minds-on" experiences embedded within constructivist approaches to science learning (National Research Council 1996, p. 13). Students can become drivers of their learning when given the opportunity to construct their own questions related to the science content they are investigating. Key to effectively preparing teachers to teach through inquiry requires improving their pedagogical content knowledge while experiencing authentic science investigations and experimentation practices. Powell-Moman and Brown-Schild (2011) note that "in-service teachers see direct benefits when scientist-teacher partnerships associated with professional development are used to develop content knowledge, along with scientific process and research skill through collaboration on research projects" (p. 48).

Pulley #3: technological literacy

Fully understanding the "T" in STEM education seems to escape many educators who fail to move beyond merely the use of educational technology to enhance STEM learning experiences (Cavanagh 2008). STEM educators with only this view point fail to acknowledge that technology consists of a body of knowledge, skills, and practices. The term *technology* means so many different things to people rendering the term almost useless, and further study of technology definitions will not bring clarity to the subject (Barak 2012). Herschbach (2009) suggested there are two common views of technology; an engineering view of technology and a humanities perspective of technology. The *engineering view*, also referred to as the instrumental perspective (Mitcham 1994; Feenberg 2006), indicates that "Technology is equated with the making and using of material objects—that is, artifacts" (p. 128). However, the *humanities view* of technology focuses on the human purpose of technology as a response to a specific human endeavor; therefore, it is the human purpose that provides additional meaning for technology (Achterhuis 2001; Mitcham 1994). The humanities view of technology recognizes that technology is value-laden (Feenberg 2006) and thus, provides opportunities to explore technology impacts including cultural, social, economic, political, and environmental (ITEA 2000).

Table 1 provides critical elements of distinction between these two views of technology.

Mitcham (1994) combines these two views together when he identified four different ways of conceptualizing technology. He identifies technology as (a) objects, (b) knowledge, (c) activities, and (d) volition. Often, people associate technology as artifacts or objects; unfortunately, many only view technology in this way and overcoming this limited view of technology may be critical for teaching STEM in an integrated approach. Mitcham also contends that technology consists of specific and distinct knowledge and therefore is a discipline. He views technology as a process with activities that include designing, making, and using technology. Technology as volition is the concept that technology is driven by the human will and as a result is embedded within our culture driven by human values. Herschbach (2009) contends that technology leverages knowledge from across multiple fields of study. DeVries (2011) in Barak (2012) writes:

> Engineering can differ from technology in that engineering only comprises the profession of developing and producing technology, while the broader concept of technology also relates to the user dimension. Technologists, more than engineers, deal with human needs as well as economic, social, cultural or environmental aspects of problem solving and new product development. (in Barak 2012, p. 318)

Barak (2012) suggests that both engineering and technology are so closely related that they should be taught in unison within technology education and suggests teaching them as one school subject called Engineering Technology Education (ETE).

In 2000, the International Technology Education Association (ITEA) drafted the *Standards for Technological Literacy*: *Content for the Study of Technology* (STL) to define the content necessary for K-12 students to become technologically literate citizens living in the twenty-first century. The STLs have been revised twice (ITEA 2002, 2007) and also include student assessment and professional development standards (ITEA 2003). The *Standards for Technological Literacy* identify content standards for grades K-12 that provide students opportunities to think critically about technology beyond technology as an object and in doing so prepare students to become technologically literate. STEM educators should provide students opportunities to think through technology as a vehicle for change with both positive and negative impacts on culture, society, politics, economy, and the environment.

Pulley #4: mathematical thinking

Studies have shown that students are more motivated and perform better on math content assessment when teachers use an integrated STEM education approach. A recent study found that students performed better on post math content assessments and increased STEM attitudinal scores when engaging in learning activities that included engineering design and prototyping solutions using 3D printing technology (Tillman et al. 2014).

Table 1 Two views of technology

Engineering perspective of technology	Humanities perspective of technology
Technology consists of:	Technology can be viewed as:
• A distinct body of knowledge	• More than a sum of tools, instruments, artifacts, processes, and systems
• An activity or a way of doing	• Influences the structure of the cultural/ social order regardless of its user intentions
• Design, engineering, production, and research procedures	• Serving human values and influence value formation
• Physical tools, instruments, and artifacts	• Autonomous social and economic forces that often override traditional and competing values
• Organized integrated systems and organizations that are used to create, produce, and use technology	• Capable of unanticipated positive as well as destructive social and economic consequences

Based upon Herschbach 2009

Williams (2007) noted that contextual teaching can give meaning to mathematics because "students want to know not only how to complete a mathematical task but also why they need to learn the mathematics in the first place. They want to know how mathematics is relevant to their lives" (p. 572). Incorporating STEM practices that include mathematical analysis necessary for evaluating design solutions provide the necessary rational for students to learn mathematics and see the connections between what is learned in school with what is required in STEM career skills (Burghardt and Hacker 2004). The authors again acknowledge that not all secondary education math content can be applied to engineering design approaches. Similarly, secondary education students may not have the cognitive development necessary to connect mathematical thinking within all engineering design problems.

The rope: a community of practice

Additionally, the concept of learning as an activity not only leverages the context of the learning but also the social aspect of learning. Lave and Wenger (1991) describe this as *legitimate peripheral participation* when the learning takes place in a community of practitioners assisting the learner to move from a novice understanding of knowledge, skills, and practices toward mastery as they participate "in a social practice of a community" (p. 29).

> In a community of practice, novices and experienced practitioners can learn from observing, asking questions, and actually participating alongside others with more or different experience. Learning is facilitated when novices and experienced practitioners organize their work in ways that allow all participants the opportunity to see, discuss, and engage in shared practices. (Levine and Marcus 2010, p. 390)

Integrated STEM education can create an ideal platform to blend these complementary learning theories by providing a community of practice through social discourse. As educational leaders have wrestled with the concept of integrating STEM disciplines, key elements of situated learning have emerged. For example, Berlin and White (1995) argued that efforts to integrate mathematics and science should be founded, in part, on the idea that knowledge is organized around big ideas, concepts, or themes, and that knowledge is advanced through social discourse.

When engaging students into a community of practice, we suggest that the learning outcomes be grounded in common shared practices. Community of practice can provide opportunity to engage local community experts as STEM partners such as practicing scientists, engineers, and technologists who can help focus the learning around real-life STEM contexts regardless of the pedagogical approach.

Using a community of practice approach to integrated STEM can be challenging for teachers as they need to continually network with experts and be open to allowing members of the community of practice into their classroom. Additionally, not all students learn best in social settings so these students may struggle to fully engage in a community of practice and this may limit their ability to learn using this educational approach.

STEM community of practice

The Next Generation Science (NGS) Framework (NRC 2012) carefully uses language that describes common practices of scientist and engineers. These practices become science learning outcomes for students. Equally important to learning science concepts, scientific practices and skills are also emphasized as key outcomes (NRC 2012). Engineering practices are also identified within the NGS framework because some of the practices of scientists and engineers are shared. An integrated STEM approach can provide a platform through a community of practice to learn the similarities and differences of engineering and science. Table 2 shows descriptions of common science practices and engineering practices providing opportunity to compare similarities and differences (NRC 2012).

The study of STEM practices can provide a better understanding of each domain and help teachers identify key learning outcomes necessary to achieve STEM learning. Table 3 below identifies key practices that build the unique set of knowledge, skills, as well as a unique language to form common practices of science and technology while investigating and solving problems (Kolodner 2002).

Table 4 identifies the math standards for math practice located in the Common Core standards for mathematics identifying common practices necessary when solving mathematical problems. Understanding these mathematical practices can be critical for effective integrated STEM education because mathematical analysis can be found in all the other STEM domains.

Upon review of these practices across science, engineering, technology, and mathematics, the very nature of these disciplines as well as the context in which the practices occur provide the learner with authentic examples that could help to illustrate crosscutting STEM connections. Locating intersections and connections across the STEM disciplines will assist STEM educators who understand these practices and how they are uniquely similar and different. An integrated STEM approach should leverage the idea that STEM content should be taught alongside STEM practices. Both content and practices are equally important to providing the ideal

Table 2 Comparison of science and engineering practices

Science practices	Engineering practices
Begins with a question about a phenomenon.	Begins with a problem, need, or desire that leads to an engineered solution.
Using models to develop explanations about natural phenomena.	Using models and simulations to analyze existing solutions.
Scientific investigation in field or lab using a systematic approach.	Engineering investigation to obtain data necessary for identifying criteria and constraints and to test design ideas.
Analyzing and interpreting data from scientific investigations using a range of tools for analysis (tabulation, graphical interpretation, visualization, and statistical analysis) locating patterns.	Analyzing and interpreting data collected from tests of designs and investigations to locate optimal design solutions.
Mathematical and computational thinking are fundamental tools for representing variables and their relationships. These ways of thinking allow for making predictions, testing theory, and locating patterns or correlations.	Mathematical and computational thinking are integral to design by allowing engineers to run tests and mathematical models to assess the performance of a design solution before prototyping.
Constructing scientific theory to provide explanations is a goal for scientists and grounding the explanation of a phenomenon with available evidence.	Constructing designing solutions using a systematic approach to solving engineering problems based upon scientific knowledge and models of the material world. Designed solutions are optimized by balancing constraints and criteria off existing conditions.
Arguments with evidence is key to scientific practices by providing a line of reasoning for explaining a natural phenomenon. Scientists defend explanations, formulate evidence based on data, and examine ideas with experts and peers understandings.	Arguments with evidence is key to engineering for locating the best possible solutions to a problem. The location of the best solution is based on a systematic approach to comparing alternatives, formulating evidence from tests, and revising design solutions.

context for learning and the rationale for doing so. Locating crosscutting practices will help students identify similarities in the nature of work conducted by scientists, technologists, engineers, and mathematicians and could help students make more informed decisions about STEM career pathways.

Discussion

Integrated STEM research agenda

The proposed conceptual framework must be tested through educational research methods to determine if these concepts improve the teaching and learning of STEM content. A research agenda must be crafted to test theories under a variety of conditions to determine the best approach to integrated STEM. In the USA, the *Committee on Integrated STEM Education* developed several recommendations directed at multiple stakeholders in integrated STEM education including those designing initiatives for integrated STEM, those developing assessments, and lastly for educational researchers (NAE and NRC 2014). For further investigation in integrated STEM education, researchers need to document in more detail their interventions, curriculum, and programs implemented, especially how subjects are integrated and supported. More evidence needs to be collected on the nature of integration, scaffolding used, and instructional designs applied. Clear outcomes need to be identified and measured concerning how integrated STEM education promotes learning, thinking, interest, and other characteristics related to these objectives. Research focused on interest and teacher and student identity also needs to address diversity and equity, and include more design experiments and longitudinal studies (NAE and NRC 2014). Though these

Table 3 A selection of science and technology skills and practices

Science skills and practices	Technology skills and practices
Understanding a problem and what might need to be investigated	Identifying criteria, constraints, problem specifications
Generating questions that can be investigated	"Messing about" with and understanding materials
Investigation with a purpose-experimentation, modeling, learning from cases, managing variables, accurate observation and measuring, seeing patterns,…	Investigation for the purpose of application-designing and running models, reading and learning from case studies,…
Informed decision making, reporting on justifying conclusions	Informed decision making, reporting on and justifying design decisions
Iteration toward understanding	Iteration toward a good enough solution
Explaining scientifically	Explaining failures and refining solutions
Investigation planning	Prioritizing criteria, trading them off against each other, and optimizing
Communication of ideas, results, interpretations, implications, justifications, explanations, principles	Communication of ideas, design decisions, justifications, explanations, design rules of thumb
Teamwork, collaboration across teams, giving credit	Teamwork, collaboration across teams, give credit

Kolodner,2002

Table 4 Mathematical standards for mathematical practice

Make sense of the problem and persevere in solving them. Mathematically proficient students explain the meaning of a problem and looks for solution entry points.
Reason abstractly and quantitatively. Mathematically proficient students are able to decontextualize—create abstractions of a situation and represent it as symbols and manipulate.
Construct viable arguments and critique the reasoning of others.
Model with Mathematics.
Appropriate tools strategically.
Attend to precision.
Look for and make use of structure.
Look for and express regularity in repeated reasoning.

Common Core State Standards for Mathematics, p 6–8

recommendations were made in the context of the American education system, they could prove helpful in many other countries' educational systems as well.

One example: Teachers and Researchers Advancing Integrated Lessons in STEM (TRAILS)

A current National Science Foundation I-TEST project can serve as an example of research created to assess the proposed framework. Todd Kelley is the principal investigator of the TRAILS project that aims to improve STEM integration in high school biology or physics classes and technology education classes. TRAILS partners science and technology teachers during a 2-week summer professional development workshop to prepare the teachers to integrate STEM content through science inquiry and engineering design in the context of entomology. 3D printing technology is used to allow students to create engineering designed bio-mimicry solutions. Students' use mathematical modeling to predict and assess design performance. Lessons are created to address technological literacy standards and well as math and science standards. The goals of the TRAILS project are as follows:

Goal 1: Engage in-service science and technology teachers in professional development building STEM knowledge and practices to enhance integrated STEM instruction.
Goal 2: Establish a sustainable community of practice of STEM teachers, researchers, industry partners, and college student "learning assistants."
Goal 3: Engage grades 9–12 students in STEM learning through engineering design and 3D printing and scanning technology.
Goal 4: Generate strategies to overcome identified barriers for high school students in rural schools and underserved populations to pursue careers in STEM fields.

The TRAILS project research will be guided by assessing the following:

(a) Science and technology education teacher's self-efficacy in teaching STEM through an integrated STEM approach.
(b) Assessing students and teacher's awareness of STEM careers.
(c) Assess students' ability to use twenty-first century skills while creating engineering design solutions to TRAILS challenges.
(d) Assess students' growth in students' STEM career interest, self-efficacy in learning STEM content, and growth in STEM content knowledge.

We theorize that teachers will increase self-efficacy teaching these subjects after participation in the TRAILS program, and this would indicate a stronger foundation for effective teaching (Stohlmann et al. 2012). Measurements of teacher self-efficacy parallels and extends the work of Nadelson et al. (2012), and additionally measures student self-efficacy in learning STEM. Self-efficacy is a good predictor of performance, behavior, and academic achievement (Bandura 1978, 1997). Research projects like TRAILS provide researcher opportunities to explore the impact of an integrated STEM teacher professional development on teachers teaching practices as well as assess impact on students' learning STEM content. TRAILS also focuses on how the project may impact students' interest in STEM careers. This project serves as one example of how future research on integrated STEM teaching can assess teaching and learning of STEM content as well as help to identify barriers that exist in current educational systems. Projects like TRAILS are needed to help inform educational researchers and the greater STEM education community what works effectively and what does not when integrating STEM subjects in secondary education. The proposed theoretical models need to be tested and vetted within the STEM education greater community. The current TRAILS project provides an ideal platform to conduct research on this approach to integrated STEM to seek to identify the benefits as well as limitations.

Conclusion and implications

The recent STEM education literature provides rationale to teach STEM concepts in a context which is most often delivered in project, problem, and design-based approaches (Carlson and Sullivan 1999; Frykholm and Glasson 2005; Hmelo-Silver 2004; Kolodner 2006; Kolodner et al. 2003; Krajcik et al. 1998). It could prove helpful if integrated STEM educators learned the various "STEM languages" and STEM practices outlined above. The reality is secondary education in the US silo STEM subjects within a rigid structure with departmental agendas, requirements, content standards, and end-of-year examinations. If these barriers remain in education in the USA and in other nations, they may constrain the successful implementation of an integrated STEM program therefore jeopardizing the entire STEM movement.

The authors suggest that the key to preparing STEM educators is to first begin by grounding their conceptual understanding of integrated STEM education by teaching key learning theories, pedagogical approaches, and building awareness of research results of current secondary STEM educational initiatives. Furthermore, professional development experiences for in-service teachers could also provide a strong conceptual framework of an integrated STEM approach and build their confidence in teaching from an integrated STEM approach. Kennedy and Odell (2014) indicated that STEM education programs of high quality should include (a) integration of technology and engineering into science and math curriculum at a minimum; (b) promote scientific inquiry and engineering design, include rigorous mathematics and science instruction; (c) collaborative approaches to learning, connect students and educators with STEM fields and professionals; (d) provide global and multi-perspective viewpoints; (e) incorporate strategies such as project-based learning, provide formal and informal learning experiences; and (f) incorporate appropriate technologies to enhance learning.

Finally, further research and discussion is needed on integrated STEM education so that effective methodologies can be implemented by teachers in the classroom and further assess the strategies this overall framework proposes here (Stohlmann et al. 2012). The TRAILS project feature above is just one example of funded research that seeks to better identify the best conditions to teach STEM subjects in an integrated approach to teaching as well as learn what level of support students and teachers require to improve STEM education.

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Competing interests
The authors declare that they have no competing interests.

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