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K-12 STEM Education: An Overview of Perspectives and Considerations

Lynn Bryan*
Purdue University, USA
labryan@purdue.edu

S. Selcen Guzey
Purdue University, USA
sguzey@purdue.edu

Abstract

Over the last two decades, discussions, rhetoric, recommendations, and policies regarding K-12[1] STEM education have escalated among businesses and industry, policy makers, think tanks, and educators around the world. STEM education is cast as pivotal in increasing productivity, prosperity, and global competitiveness; as a lynchpin in addressing current and future socio-geo-political-economic challenges; as a panacea for filling shortages in workforce pipelines. In this commentary, we discuss the emergence of STEM acronym, its variants, and the rhetoric surrounding STEM that drives educational policy. We examine more closely the integration of STEM and present an example of how in our own work, we have begun to clarify the characteristics of integrated STEM that guide our projects. We summarize some of the research studies in the emerging field of integrated STEM that document its benefits and reflect on the opportunities afforded STEM educators for future research. This commentary is by no means exhaustive, but is intended to instigate thought, reflection, and progress regarding the nascent state of integrating the STEM disciplines.

Keywords: STEM, K-12 STEM education, integrated STEM

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Introduction

The profound, pressing, and intractable challenges facing today's global society far surpass in urgency and complexity any of the previous generations and extend far beyond any individual nation's borders. The challenges and problems that humanity faces—overpopulation, rising sea levels, loss of biodiversity, depletion of natural resources, gender bias, racism, wealth disparity, erosion of privacy, rising nationalist sentiment—are of a magnitude that no one discipline, institution, or organization can individually tackle and have arisen during an era of, or in spite of, rapidly expanding scientific and technological research and development worldwide (National Academy of Engineering, 2016).

From the early 1990's, science education, mathematics education, and technology education emerged to take a central focus in discussions, rhetoric, and recommendations among businesses and industry, policy makers, think tanks, and educators mostly from industrialized nations around the world, as a lynchpin in addressing such current and future socio-geo-political-economic challenges (European Commission [EC], 2004, 2007; Friedman, 2005; Government of Canada, 2007; National Academy of Sciences [NAS] & National Academy of Engineering [NAE], 2014; NAS/NAE/Institute of Medicine [IM], 2007; Office of the Chief Scientist, 2014; Organisation for Economic Co-operation and Development [OECD], 2008; Royal Society Science Policy Centre, 2014). In recent years, the intense focus on science, mathematics, and technology education—with the addition of engineering education—has escalated, driven in part by the fixation on global economic competitiveness, reported crises in populating a "leaky" workforce pipeline, and international mathematics and science test score comparisons, particularly on the Programme for International Student Assessment [PISA] and the Trends in International Mathematics and Science Study [TIMSS] (Australian Education Act, 2013; Figazzolo, 2009; Marginson, Tytler, Freeman, & Roberts, 2013; Office of the Chief Scientist, 2014; U.S. Department of Education, 2009).

For example, by the mid-2000's in the U.S., dire warnings appeared that "the world is flat" and there was an urgent need to enhance the nation's ability to compete in a flat world (Friedman, 2005); that "storms" were gathering (NAS/NAE/IM, 2007) and "approaching Category 5" (NAS/NAE/IM, 2010)—i.e., the advantages in the U.S. marketplace and in science and technology were eroding, and there existed an exigent need to bolster U.S. competitiveness and pre-eminence in the STEM fields. On December 6, 2010, President Obama proclaimed that "our generation's Sputnik moment is back" (Lee, 2010), and later that year, the President's Council of Advisors on Science and Technology (PCAST, 2010) announced that "STEM education will determine whether the United States will remain a leader among nations and whether we will be able to solve immense challenges in such areas as energy, health, environmental protection, and national security" (p. 1). In the same time period, the Government of Canada declared their intentions to create "a more competitive and sustainable Canadian economy with the help of science and technology. This new, focused strategy recognizes that the most important role of the Government of Canada is to ensure a competitive marketplace and create an investment climate that encourages the private sector to compete against the world on the basis of their innovative products, services, and technologies" (p. 4). In 2015, the Australian government published its *National Innovation and Science Agenda: Welcome to the Ideas Boom*, declaring that "Innovation and science are critical for Australia to deliver new sources of growth, maintain high-

[1]"K-12" is an expression used in the United States to refer to the pre-college range of years in primary and secondary education—kindergarten through 12th grade.

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* Corresponding author

wage jobs and seize the next wave of economic prosperity… Innovation keeps us competitive. It keeps us at the cutting edge. It creates jobs. And it will keep our standard of living high" (p.1).

Origins of the STEM Acronym

STEM as an acronym for science, technology, engineering, and mathematics was popularized by educators, policy makers, and researchers in the early 2000's. According to Sanders (2009), the origin of the acronym dates back to the 1990's when the U.S. National Science Foundation (NSF) began using "SMET" as shorthand for the combination of the four disciplines of science, mathematics, engineering, and technology (see, for example, Committee on Equal Opportunities in Science and Engineering, 1998). The reorganization of the composing letters of SMET occurred when an NSF program officer observed that SMET sounded too similar to smut. Thus, the acronym of STEM was born (Sanders, 2009). At the time, STEM was a conglomerate term used to refer to one or several of the constituent disciplines, but has since evolved into various interpretations beyond individual disciplines to refer to various integrated pedagogical models, approaches, and practices (Akerson et al., 2018; Bybee 2010, 2013; English, 2015). For example, in *A Case for STEM*, Bybee (2013) presents nine different models of STEM education: from a perspective of STEM being synonymous with science or a single science discipline like physics or biology, to STEM referring to a transdisciplinary approach for addressing major challenges such as global climate change or use of resources for energy. Similarly, Lederman and Lederman (in press) characterize STEM as an integrated approach to curriculum, not a discipline on its own.

In addition, there have emerged variations of the constituent disciplines to create new, related acronyms. For example, STEAM—Science, Technology, Engineering, Art, and Mathematics—has gained significant popularity in Korea, Japan, Taiwan, Australia, and the U.S. (see Allina, 2018; Lee & Chang, 2017; Perignat & Katz-Buonincontro, 2019). ST^{2}EAM—Science, Technology, Transformative learning, Engineering, Arts, and Mathematics—emphasizes transformative science education (Taylor, 2015) which cultivates "five interconnected ways of knowing, being and valuing: *cultural self-knowing, relational knowing, critical knowing, visionary and ethical knowing, knowing in action*" (Taylor & Taylor, 2018, p. 469). STEMSE— Science, Technology, Engineering, Mathematics, Societies and Environments prioritizes students' learning about social justice and environmental sustainability and preparing students to address ecojustice problems they identify (Bencze, Reiss, Sharma, & Weinstein, 2018). STEAMM— Science, Technology, Engineering, Art, Mathematics, and Medicine—is a variant predominantly used in post-secondary education discussions (e.g. Miller & Kimmel, 2012). Recently, STREAM has surfaced to refer to the integration of robotics into STEAM (Elkin, Sullivan, & Bers, 2018) as well as STEM+C to refer to the integration of computing into STEM (National Science Foundation, 2018).

The ubiquitous use of the term STEM, with little definitional consistency, runs the risk of diluting its potential value for enhancing, reforming, and informing K-12 research, policies, programs, and practices. As many variations exist of the meaning of STEM, STEM education continues to be a significant feature of reforms at the national, state, district, and school level in countries all over the world. Bybee (2010) noted, "As the use of the acronym STEM gets closer to school districts and especially classrooms, the requirements for clarity and meaning not only increase, but they become critically urgent as well" (p. 73). Rather than striving for a singular definition of STEM, it is incumbent upon researchers, policy makers, educators and other education stakeholders to articulate and clarify in their work what they mean by their use term STEM or any of its variants.

Integrated STEM

While perspectives on the nature of STEM (and its constituent disciplines) in the context of K-12 education are varied, English (2015) noted that in the last several years, education stakeholders have increasingly focused on addressing the nature of STEM *integration* and research recommendations for advancing the field (e.g., NAE/NRC, 2014; Rennie, Venville, & Wallace, 2012; Vasquez, 2014/2015). In our own work, the integration of STEM disciplines is prioritized and therefore, we use the phrase *integrated* STEM to delineate that we are referring to models of the explicit, intentional integration of core disciplinary content and practices of STEM disciplines. We believe that whether the constituent disciplines are STEM, STEAM, STEMSE, etc., the principles and characteristics of integrated STEM are applicable and transferable.

Given the focus of the recent educational reforms in engineering and technology in K-12 education (e.g. Australian Council of Learned Academies, 2013; NGSS Lead States, 2013; NRC, 2012; Royal Society Science Policy Centre, 2014), engineering/technology design has become prioritized as an essential component of science and mathematics education. While incorporating engineering into science or mathematics instruction is not new (e.g., Tasar, Taylor, & Dana, 1999; Taylor, Dana, & Tasar, 2001; Taylor, Lunetta, Dana, & Tasar, 2002), the recent broad movement to integrate engineering/technology design has entered into K-12 classrooms in a variety of forms and contexts (NAE/NRC, 2009; NRC, 2009, 2010). In some cases, engineering/technology design has been used to support science and/or mathematics instruction. In this approach, science and mathematics learning goals are foregrounded, and engineering/technology design is integrated in a manner that allows students to apply their science and/or mathematics knowledge and practices to find viable solutions for design problems. Occasionally, engineering design pedagogies are used to introduce engineering concepts and practices while also providing students opportunities to explore focal science and mathematics concepts. Integration of some or the entire group of STEM disciplines is complex and requires that teachers have a robust understanding of not only the content and practices of each of the integrated disciplines, but also the alignment and coherence among integrated STEM teaching approaches, learning goals and assessments (NAE/NRC, 2014; Wang, Moore, Roehrig, & Park, 2011). In short, the integration of STEM disciplines is much more intentional than teaching two different subjects in one lesson or using one discipline as a tool for teaching another (e.g., using an equation mathematics to determine average velocity).

Characterizing integrated STEM

Similar to efforts to define STEM, determining a precise consensus definition of integrated STEM has proven to be challenging. As the U.S. Committee for Integrated STEM Education noted in their report, *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research* (NAE/NRC, 2014), integration occurs in a variety of ways: "It may include different combinations of the STEM disciplines, emphasize one discipline more than another, be presented in a formal or informal setting, and involve a range of pedagogical strategies" (p. 23). In addition, connections between and among disciplines may occur at more than one level at the same time: "in the student's thinking or behavior, in the teacher's instruction, in the curriculum, between and among teachers themselves, or in larger units of the education system, such as the organization of an entire school" (p. 23). Such challenges reiterate the need to identify and characterize existing integrated STEM approaches, particularly as the field of integrated STEM education evolves from its early stage of development. As an example, our review of the emerging body of scholarship devoted to integrating the STEM disciplines has led us, for our own programs, to characterize integrated STEM education for K-12 classrooms based on five distinguishing, core elements as summarized in **Table 1**.

It is necessary to point out that some of these distinguishing elements define integrated STEM education more explicitly than instruction that is labeled "interdisciplinary" (e.g., interdisciplinary science, interdisciplinary studies, interdisciplinary education). Indeed, if one considers the definition of interdisciplinary studies from Newell & Green (1982)— "inquiries which critically draw upon two or more disciplines and which lead to an integration of disciplinary insights" (p. 24)—integrated STEM may be considered a form of interdisciplinary instruction. In addition, the distinguishing characteristics define integrated STEM education more explicitly than instruction that integrates, for example, science and mathematics. A large body of literature exists addressing the importance and benefits of integrating science and mathematics instruction (Czerniak, Weber, Sandmann, & Ahern, 2010). Integrated STEM instruction, on the other hand, employs engineering/engineering design as the integrator and requires design justification through the use of scientific and mathematical concepts as an essential feature.

Our view of integrated STEM education is influenced by our teaching and research experiences and knowledge of education theories, research, programs, curriculum, and reforms. These features of integrated STEM education for K-12 classrooms allow for substantive opportunities for students to actively engage in their learning; develop new understandings, practices, and skills; and recognize the interdependence among science, technology, engineering, and mathematics in more contextualized, relevant, and locally and globally meaningful instructional environments (Gilbert, 2006; Sjøberg & Schreiner, 2010)

Table 1. Distinguishing elements of integrated STEM (Adapted from Bryan, Moore, Johnson & Roehrig, 2015)

Distinguishing Elements	Description
The content and practices of one or more *anchor STEM disciplines* define the primary learning goals.	Anchor disciplines are the primary disciplines from which the main learning goals for instruction are derived. Learning goals provide coherence between the instructional activities and assessments. (Wiggins & McTighe, 2005).
The integrator is typically is the *practices of engineering and engineering design* as the context and/or an intentional component of the content to be learned.	An "integrator" brings together different parts in a way that requires those parts to work together for a whole. As the integrator, the practices of engineering and engineering design provide real-world, problem-solving contexts for learning and applying disciplinary content and practices. In addition, engineering practices require students to use informed judgments to make decisions and help them develop habits of mind such as troubleshooting, drawing from prior experiences, and learning from failure (Johnston, Akarsu, Moore, & Guzey, 2019; Morrison, 2006).
The engineering design or engineering practices related to relevant technologies requires the scientific and mathematical concepts through *design justification.*	Design justification is one way to require the students to apply the disciplinary understandings to the engineering design. For example, students should make recommendations for design decisions that are supported by the background information and content as well as results/data from tests. Justification of design choices is parallel to the argumentation in science education, i.e., claims, evidence, explanation (Toulmin, 2008; see also Hand, Norton-Meier, Staker, & Bintz, 2009; Llewellyn, 2014).
The development of *21st century skills* is emphasized.	The phrase, "21st century skills," refers to the knowledge, skills, and character traits that are deemed necessary to effectively function as citizens, workers, and leaders in the 21st century workplace (Bybee, 2010; NRC, 2012; Partnership for 21st Century Skills, 2011).
The context of instruction requires *solving a real-world problem or task* through teamwork and communication.	A real-world problem or task centers on an authentic issue or meaningful challenge. As opposed decontextualized or contrived tasks (for example, "cook-book" labs or rote problem solving), real-world problems, whether structured or ill-structured, engage students in issues that are significant in everyday life and have personal and/or social relevance. Furthermore, the teamwork involved in solving real-world problems or tasks provide opportunities for students to understand the interdisciplinary nature of STEM through rich, engaging, and motivating experiences. Teams of students communicate their design processes, decisions, and results (Brophy, Klein, Portsmore, & Rogers, 2008; Carlson & Sullivan, 2004; Chin & Chia, 2006; Moore et al., 2014).

Integrated STEM teaching and learning

Establishing the purposes of STEM education is not an insignificant exercise, as the way we conceptualize its purposes frames the way that we think about and design STEM teaching and ultimately drives the development of learning goals. For example, if STEM education is to prepare all students to learn to apply the core ideas and practices of the STEM disciplines to phenomena and life situations, to help students develop knowledge and skills that transcend disciplinary boundaries necessary to solve today's complex problems, then integration is necessary and understanding the nature of the STEM disciplines is critical. Each discipline has its own culture, practices, and ways of knowing and sharing knowledge. These important differences among disciplines can guide the ways in which educators teach disciplinary content and practices. For example, science is a process of articulating, testing, evaluating, and refining or revising models of the natural world. The questions scientists ask or the ways that they collect and analyze data and share their findings with the scientific community are different than the questions mathematicians ask and how they study such questions or communicate ideas and findings. Mathematicians study numbers, quantities, and spaces, and they make claims using logical arguments, while scientists find empirical evidence to warrant their claims (NAE/NRC, 2014). According to Hudson and colleagues (in press), three important aspects of mathematics will support students' understanding of the nature of mathematics. These aspects include that mathematics is (1) a way of knowing; (2) tentative, as mathematical claims are based on assumptions; and (3) a creative endeavor. Similarly, science is a way of knowing, tentative, and a creative endeavor (NGSS Lead States, 2013).

Engineering, on the other hand, concerns design and problem solving and applies concepts from science and mathematics to solve problems that humans are experiencing. Using design processes, engineers design products or processes, following design criteria and working under constraints. Engineers use knowledge, skills, and habits of mind including creativity, systems thinking, collaboration and communication, optimism, and ethical considerations (NAE/NRC, 2009; National Academies of Sciences, Engineering, and Medicine, 2020). Furthermore, engineers use existing technology tools or develop new technologies to solve problems. Scientists and mathematicians also produce technology and use technology tools. Technology, then, "while not a discipline in the strictest sense, comprises the entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artifacts, as well as the artifacts themselves" (NAE/NRC, 2014, p.14). Clearly, there are similarities and differences among the disciplines of science, technology, engineering, and mathematics, and understanding the nature of one contributes to understanding others (Dugger, 1993).

However, understanding culture, practices, and ways of knowing and sharing knowledge of the STEM disciplines constitutes only part of the path to integration. One of the key challenges in integrated STEM teaching and learning is connecting core content knowledge and processes *across* the disciplines (English, 2015). Students need opportunities to engage in discipline specific practices, while at the same time recognizing and understanding how the individual disciplinary knowledge, skills, and practices support and inform each other. Problem- and project-based approaches (Barron et al., 1998; Blumenfeld et al., 1991; Hmelo-Silver, 2004) are commonly used in integrated STEM education. Both problem- and project-based learning approaches focus on providing learning experiences that incorporate inquiry, problem-solving, creativity, and other 21st Century (Partnership for 21st Century Skills, 2011) skills to design solutions to an open-ended question, problem, or challenge (Blumenfeld et al., 1991; Roth 2001). Students work collaboratively, utilize multiple tools, and collect and analyze various data sources to solve the question, problem, or challenge. It is essential with integrated STEM learning that the pedagogy that drives instruction has an integrated focus that deepens students' understanding of core ideas and practices in the STEM fields and of concepts and practices that are shared across the STEM fields, while engaging and sustaining students' interest with an important topic, problem, or issue that has real-world applications (NRC, 2011).

Finally, an emerging trend in integrated STEM teaching and learning that is showing promise for fostering the creating, designing, and innovating aspects of STEM is the "maker movement" (see Halverson & Sheridan, 2014). According to Halverson and Sheridan (2014), the maker movement "refers broadly to the growing number of people who are engaged in the creative production of artifacts in their daily lives and who find physical and digital forums to share their processes and products with others" (p. 496). As part of this movement, a growing number and diversity in types of makerspaces are becoming popular features in both formal and informal STEM learning environments (Peppler & Bender, 2013; Sheridan, Halverson, Brahms, Jacobs-Priebe & Owens, 2014). Making and makerspaces are seen as a potential way of expanding opportunities for participating, and hence learning, in STEM education; re-envisioning and expanding the learning outcomes (e.g., practices and mindsets) of STEM education; and enriching the experience of learning in STEM by encouraging students' identity development as a member of a community of practice (Calabrese Barton, Tan, & Greenberg, 2017; Sheridan et al., 2014). We are just beginning to learn how makerspaces are used, incorporated into, and changing the siloed structure of classrooms, particularly in middle and high schools[2].

[2] "Middle school" is an expression used in the United States to refer typically to Grade 5 or 6 through Grade 8. "High school" is an expression used in the United States to refer typically to Grades 9 through 12

Benefits of integrated STEM education

While the number of studies is limited, several have shown the benefits of integrated STEM education and the positive effects of student engagement in STEM activities in K-12 classrooms (e.g., English, 2017; Guzey, Harwell, Moreno, Peralta, & Moore, 2017; Lachapelle & Cunningham, 2014; Means et al., 2017; Wendell & Rogers, 2013). In its report, the Committee on Integrated STEM Education reviewed research related to student outcomes and identified the impact of integrated STEM education in two areas; student learning and interest and identity development (NAE/NRC, 2014). A growing number of studies show the positive impact that integrated STEM has on science learning (Gardner & Tillotson, 2019; Guzey & Aranda, 2017) and mathematics learning (English & King, 2019) when engineering and technology are meaningfully integrated with science and mathematics instruction. Effective integration of STEM instruction occurs when the constructs and skills of the disciplines productively and meaningfully interact and support students' learning of science, mathematics and engineering/technology and their interconnections. The goal of effective integrated STEM education is not simply adding on engineering/technology to existing science and mathematics curriculum, rather explicitly and systematically embedding engineering/technology into science and mathematics instruction and vice versa.

In addition, research shows the positive impact that integrated STEM education has on students' interest and identity development (e.g., Calabrese-Barton, Tan, & Greenberg, 2017; Guzey, Harwell, Moreno, Peralta, & Moore, 2017; Kim, Sinatra, & Seyranian, 2018; Lachapelle & Cunningham, 2014). Previous studies have shown that students start developing interest in STEM before middle school (Maltese & Tai, 2010). High interest in STEM in the middle or high school is consistently associated with increased intent to pursue a degree in STEM fields (Maltese, Melki, & Wiebke, 2014). However, it has been found that interest in STEM declines in middle school (Maltese & Tai, 2010; Osborne, Simon & Collins, 2003; Tai, Liu, Maltese, & Fan, 2006). This drop in interest in STEM has been found to be more frequent among female students than male students (Tytler, 2014). Vedder-Weiss and Fortus (2012) demonstrated that student motivation and interest are driven mainly by the school environment rather than by home environment. The inclusion of learning activities that are interesting to students and that are connected to their everyday experiences is important for increasing interest in STEM subject and pursing STEM careers.

Suggestions for Future Scholarship on Integrated STEM Education

While the integration of STEM disciplines offers rich, varied, innovative and creative approaches to K-12 classroom instruction, many unanswered questions offer rich, varied, innovative and creative opportunities for future scholarship. In this section, we broadly refer to "STEM" and "STEM education" to include an integrated STEM vision as characterized in **Table 1**, as well as variants of STEM (as discussed above). We chose three broad areas of STEM education research for focusing our discussion of suggestions for future scholarship (see **Figure 1**), recognizing that these areas are inherently connected to each other and so clearly demarcated.

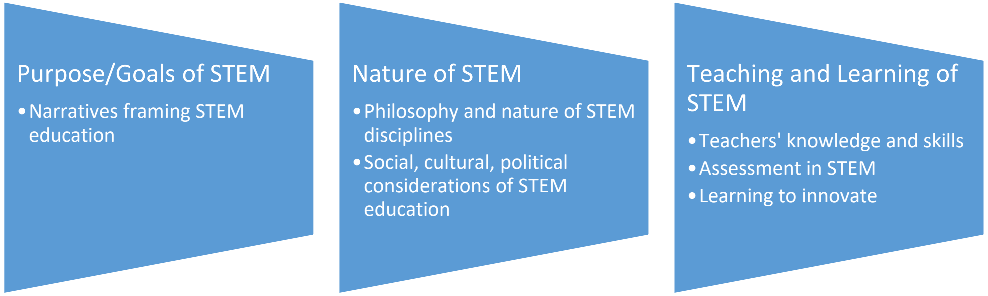

Figure 1. Suggestions for future STEM education research

Purpose/goals of STEM: Narratives framing STEM education

One critical area of scholarship that we feel must be addressed is the nature of the narratives framing STEM education scholarship. Providing students with rich educational experiences to develop knowledge and skills that transcend disciplinary boundaries necessary to solve today's complex grand challenges is indeed essential to preparing individuals for a STEM workforce. However, ideological pronouncements framed in terms of global competition, privilege, and power, instinctively should lead STEM education scholars to seriously consider and reflect upon the purposes, goals, and outcomes (intended and unintended) of STEM education (see Avraamidou & Bryan, 2018).

Future scholarship on integrated STEM can repeat such utilitarian rhetoric or be a part of changing the rhetoric. We call for countering such narratives and demonstrating that the purpose of STEM education as far greater than serving economic or technological goals, far greater than a myopic vision of outperforming all other nations on international tests, preparing more students to enter STEM workforce, or propelling any one nation to global dominance. For example, an emerging body of scholarship is focusing on students' development of expertise and motivation for implementing sociopolitical actions with the purpose of benefitting the well-being of individuals, societies, and environments and creating a more equitable, humane, and sustainable world (e.g., Amat, 2019; Bencze et al., 2018; Carter, Rodriguez, & Jones, 2018; Kim, Rasporich, & Gupta, 2019; Pouliot, 2019; Tan, Calabrese Barton, & Benavides, 2019). Contrary to a utilitarian perspective rooted in competition and division, such perspectives highlight *relational* goals and purposes of STEM education in which students develop an understanding of what is happening in the world and how scientific phenomena affect our lives, the lives of others, and their ability to participate as global citizens in a world that is rapidly changing (Avraamidou & Bryan, 2018).

Questions Regarding the Nature of STEM

One area of scholarship and debate around STEM integration is the question of whether or not there is a "nature of STEM" as separate and distinct from the nature of the STEM disciplines (e.g., Peters-Burton, 2014; Akerson et al., 2018). As a precursor to considering a nature of STEM, scholars and practitioners may reflect on questions regarding the philosophy and nature of the STEM disciplines and the social, cultural and political considerations of STEM education. The increasing attention given to the questions regarding the philosophy and nature of STEM disciplines will lead to better understand and conceptualize the integration of STEM disciplines. As recommended by the committee for *STEM Integration in K-12 Education,* "researchers, program designers, and practitioners focused on integrated STEM education, and the professional organizations that represent them, need to develop a common language [and understanding of STEM] to describe their work" (NAE/NRC, 2014, p. 8) that would allow meaningful improvement in STEM education

Philosophy and nature of STEM disciplines

An area of scholarship that should inform the goals and purposes of STEM education is the philosophy and nature of the STEM disciplines—the epistemologies, ontologies and methodologies of the individual disciplines as well as the implications for integration of STEM disciplines. STEM disciplines have many aspects in common, but each has distinctive features as well. While each discipline values creativity, critical thinking, and logic, the way knowledge is formed and communicated differs from discipline to discipline. For example, particular scientific practices (e.g., observing, conducting experiments) scientists engage represent the aspects of the nature of science. The nature of technology represents knowledge of what technology is and how it involves and the nature of mathematics represent the mathematical process and thinking. Both knowledge about the nature of technology and nature of mathematical thinking are necessary for scientific endeavor (American Association for the Advancement of Science [AAAS], 1990). The integration of STEM disciplines then raises compelling questions regarding the philosophical traditions of science, technology, engineering, and mathematics (as well as art, medicine, computing, etc.) (e.g., Cullen & Guo, in press; Hudson, Creager, Burgess, & Gerber, in press). For example, what does each discipline claim about the nature of reality? About the relationship between the knower and the known? About the nature of causal relationships, the nature of generalization, and the role of values? Where are points of congruence and/or incongruence? How can the philosophy and nature of the STEM disciplines be reflected in integrated STEM instruction such that students may begin to understand and appreciate the role of different practices and ways of reasoning? Further, how can integrated STEM education take into consideration diverse ways of knowing and describing the natural world among diverse sociocultural groups (e.g., aboriginal and indigenous communities' ways of relating to the nature) that may differ from dominant perspectives? (Avraamidou, Kayumova, & Adams, 2019).

Social, cultural, and political considerations of STEM education

Related to the call for defining and characterizing what one means by STEM, it should be recognized that the meaning and variants of STEM education have largely been conceptualized based on Western perspectives and that constructs used in STEM discourse do not carry universal meanings. For example, Nicole Karafyllis (2015) explained that the Arab world lacks the specific Western concept of "technology" and that "it still is a common misunderstanding of (mostly) Western scientists, engineers and politicians that technologies and their related objects encompass, generally speaking, universal functions and hence also have universal meanings" (p. 3). A future direction of research and scholarship in STEM education should consider sociocultural views of STEM disciplines as well as the assumptions embedded in "Western STEM." In an age of hyperconnectivity, what kinds of cross-cultural frameworks can inform and advance STEM education in all part of the world?

Further, we cannot ignore the implications of increasing ethnic, racial, cultural, linguistic, socioeconomic, and religious diversity in classrooms around the world as a result of unprecedented levels of global migration and forced displacement (see OECD, 2019). While STEM education continues to grow in terms of its societal importance, research continues to grow in terms of documenting how diverse learners, particularly those from economically disadvantaged communities, continue to be underrepresented in and have inequitable access to high-quality STEM learning experiences (Calabrese Barton & Tan, 2018; NRC, 2012). How will STEM educators and researchers inquire into intellectually and socially significant issues about race, culture, language, religion, and socioeconomics? How can STEM instruction be designed that integrates what we learn about the complex sociocultural world in which children construct knowledge in the classroom, outside of the classroom, and prior to coming to new classrooms? What are ways in which STEM educators and researchers can learn from the children's antecedent experiences and the local expertise that resides in their communities to create STEM learning spaces in which diverse groups of students may meaningfully participate? According to Avraamidou, Kayumova, and Adams (2019), a paradigm shift is needed:

> …where researchers adopt multiple sociocultural and diverse theoretical lenses, rooted in sociocultural, critical, and radical approaches, epistemologies and ontologies (i.e., critical race theory, radical feminism, anticolonial theory), and/or consider bringing theoretical perspectives into conversation with one another in novel ways that when examining learners participation in, and relationship to [STEM], as an alternative prism that allows us to look into students' lives and to address goals related to equity, diversity, and power differentials. (p. 289)

Scholarship from new and diverse theoretical perspectives has the potential to inform STEM education policies that build an agenda more closely aligned with addressing the needs and priorities for those whom the policies are intended to serve.

Teaching and Learning of STEM

Since the integrated STEM education approaches are different from the traditional approaches to teach STEM disciplines, research exploring the innovative approaches such as integration of scientific investigations and engineering design is critical for improving student learning outcomes. Evidence-based, research supported understandings of how students learn should be used as the basis for the development of curricular materials and STEM instruction. While a wide variety of factors impact students' STEM learning outcomes and they need to be studied in the context of integrated STEM education, here, we focus on only three areas of research: teacher knowledge and skills, assessment, and learning to innovate.

Teachers' development of knowledge and skills for integrated STEM instruction

Content knowledge, pedagogical knowledge, and pedagogical content knowledge are important components of teaching effectively. What do STEM teachers and STEM teacher educators need to know integrate multiple STEM disciplines using appropriate pedagogies in ways that reflect an understanding of "how students' learning develops in [a given] field…and strategies for addressing students' evolving needs" (NRC, 2010, p. 73)?

Although a very large number of variables could influence the learning and implementation of integrated STEM education approaches, the small amount of available data for teachers who are integrating multiple STEM disciplines suggests that appropriate content knowledge in more than one STEM subject, an ability and confidence to teach multiple STEM disciplines, and knowledge of evidence-based instructional practices and pedagogical strategies for instruction in engineering are key factors in preparing and supporting teachers to successfully implement integrated STEM education (Hynes, 2010; Johnston et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2018; Wang et al., 2011). Moreover, STEM teacher education programs need to support teachers in becoming informed, resourceful practitioners when addressing issues of diversity in their classroom. Teachers need opportunities to develop perspectives on and access to the broad and rich personal experiences and community-based resources that their diverse students bring to the STEM classroom (Bryan & Allexsaht-Snider, 2008).

To help teachers deliver integrated STEM instruction, teacher education and professional development programs should provide opportunities for teachers to have experiences for building pedagogical approaches to integrated STEM education that are culturally responsive, respectful, and effective; that reflect an understanding of sociocultural processes and discourse practices of learning. This would require many universities to update or revise the design of their teacher preparation programs to model appropriate pedagogies for integrated STEM education that teacher candidates will use in their own classrooms. Teaching methods courses for integrated STEM instruction, STEM seminars (Bergsten & Frejd, 2019) designed to help pre-service teachers explore different integrated teaching have found to be helpful in developing STEM lessons. Preparing teachers who are effective and confident in teaching multiple subjects using appropriate, culturally responsive pedagogical strategies is challenging, but it is critical for the widespread implementation of integrated STEM education.

Apart from learning opportunities for teachers, financial resources and administrative support play a role in implementing STEM experiences in schools. The structures of siloed classrooms and disciplines often inhibit efforts to integrate multiple disciplines, and teachers need financial and administrative support to break the barriers of such a structure. What will be required to accomplish the profound restructuring of deeply entrenched school structures and curricula, especially at the middle and high school levels, to implement integrated STEM instruction in K-12 schools and classrooms?

Assessment in STEM education

As the body of scholarship on STEM integration evolves, challenges naturally are arising in how to capture the impact of instruction, i.e., the outcomes of integrated STEM education. As integrated instruction ideally seamlessly embeds content and practices into instruction, tools are needed that can effectively assess learning experiences. What are the key indicators of students' learning with respect to the content, skills, and practices of the constituent disciplines in an integrated STEM (or any of the STEM variants) context? What are key indicators of students' understandings of interdisciplinary connections? What are the key indicators of students learning with respect to the relational, social, and/or activist goals of STEM instruction? What are ways in which we can design assessments that allow emergent bilingual or multilingual students to demonstrate and articulate their learning? What are ways in which the previous questions can be addressed so as to disrupt the deficit discourse that often frames assessment? There exists a critical need in developing a variety of valid, reliable measures that would allow researchers to better understand and evaluate integrated STEM teaching and learning.

Interest and motivation are also commonly used indicators to capture impact of integrated STEM education. However, as the Committee for Integrated STEM Education noted, "research studies vary in considerably in quality and often do not take into account the different phases of interest development" (NAE/NRC, 2014, p. 3). Furthermore, existing instruments that measure interest development pay little attention to context, duration, size, and nature of STEM programs. Studies on interest development are commonly used in out-of-school STEM programs to report the contributions of such programs to students' interest in STEM. It is important to stress that the researchers need to develop instruments not only to provide evidence for the impact of informal learning experiences, but also to document criteria of successful programs that produce positive outcomes and practices, and to determine how and under what circumstances these programs support students from culturally, linguistically, and socioeconomically diverse backgrounds and experiences. Furthermore, studies of interest and motivation should be built on models and theories that describe people's motivational drivers. For example, Self Determination Theory proposed by Deci and Ryan (1985), examines the intrinsic and extrinsic motivation and motivational factors that influence human behavior. In the context of integrated STEM education, studying the conditions or STEM program components that elicit and sustain intrinsic motivation of students or the external factors that help students acquire the motivation to engage in STEM could guide educators to design better programs.

Additionally, as educators, curriculum developers, and researchers use different models or approaches to integrated STEM education, it becomes a challenge to synthesize and/or compare program outcomes across different studies. Scholarship should clearly define and characterize not only indicators and evidence of learning, but also a working definition of STEM/STEM education and the framework that grounds the model or approach to curriculum, professional development, or any other programs such as informal or out-of-school STEM learning experiences. Doing so may illuminate important models, approaches, or contexts of integrated STEM instruction that lead to student learning. Moreover, recent research shows that the extent of the impact of the integrated STEM instruction on learning varies by science domain and instruction (Guzey, Harwell, Moreno, Peralta, & Moore, 2017; Wendell & Rogers, 2013). Future studies may shed light on if and how integrated STEM education may bolster student learning as compared to disciplinary or interdisciplinary instruction that does not specifically aim to integrate engineering to science and/or mathematics.

Finally, given that many policy decisions rest on international test comparisons (see for example, Figazzolo, 2009; Froese-Germain, 2010; Gorur & Wu, 2015), it would prudent to not only systematically examine the results of these tests and how data are interpreted, but also critique how such tests reflect (or do not reflect) the purposes and learning goals of integrated STEM. In addition, such scholarship needs to be seen by those who create education policies and make decisions that come to bear on the future of STEM education.

Teaching and learning to innovate in K-12 STEM

As mentioned previously, one increasingly popular context in which the teacher and learning of STEM is taking place is makerspaces. Makerspaces are touted as a site for fostering a mindset of innovation and creativity in educational settings (Peppler & Bender, 2013). Makerspaces are becoming features of K-12 schools that can afford to have one, but we know little about how they are used, integrated into, and changing the siloed structure of classrooms, particularly at the middle and high school level.

Innovation, idea generation and insightful problem solving rely on productive thinking, which is "characterized by shifts in perspective which allow the problem solver to consider new, sometimes transformational, approaches" (Foster & Yaoyuneyong, 2016, p. 42). In stark contrast, much of K-12 science and mathematics instruction is designed for re-productive thinking— "the application of familiar, routine, procedures" (Foster & Yaoyuneyong, 2016, p. 42). Fostering innovation requires, among other attributes, being able to fluently generate original ideas, tolerate ambiguity, and imaginatively elaborate (Torrence, 1977). Furthermore, Tan (2019) warns of relying too heavily on "technocratic rationalities which fundamentally misunderstand the nature of innovation, learning, and human (and non-human) agency" (p.203). Amidst the eagerness to add makerspaces to K-12 schools, it is incumbent upon STEM educators to consider: What purpose do makerspaces serve—what are the goals and purposes of making, particularly as making is related to STEM learning? Beyond goals for content and practices, the maker movement inspires opportunities to consider goals/purposes related to, for example, making quality STEM learning experiences more accessible, inclusive, and equitable. As makerspaces are incorporated into STEM teaching and learning environments, we also need to examine what constitutes meaningful makerspace experiences. How are productive thinking, creativity and innovation fostered, especially in the current pressurized climate of K-12 schooling where anything to be learned is known in advance in order to align high-stake assessments with curriculum and instruction. Where do makerspaces fit into such a climate when innovating (and learning to innovate) means for example, being open to ambiguity and failure?

Final Thoughts

Over the last two decades, STEM education, and more recently the integration of STEM disciplines, has received increasing attention and prioritization in countries around the globe. In this brief commentary, we have discussed the emergence of the STEM acronym and its variants, including the trend toward more substantial and meaningful integration of STEM disciplines, sharing how in our own work, we have derived research-based, distinguishing characteristics of integrated STEM that guide our projects. We summarized a few of the growing number of research studies in integrated STEM that document its benefits. Given that integrated STEM is in its "embryonic stages" (English, 2016, p. 3), there is still a great deal that educators, researcher, policy makers, etc. can and should learn about the nature, design, implementation and outcomes of integrated STEM education. Thus, we touch on just a few of the abundant opportunities afforded STEM educators for future research. This brief commentary is not intended to be an exhaustive review, synthesis or summary of literature, but rather to instigate thought, raise issues, and prompt reflection about the challenges and possibilities of STEM education in making a positive impact on students' learning and their participation as global citizens in a world of accelerating change.

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