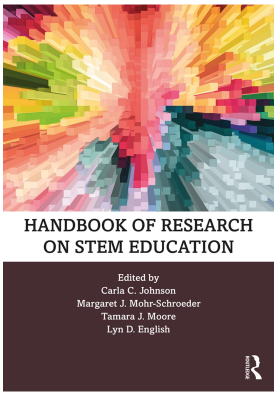

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10

SECONDARY STEM LEARNING

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Secondary education is an important period in which adolescents negotiate and develop their academic and career trajectories (Ogle, Hyllegard, Rambo-Hernandez, & Park, 2017; Nugent, Barker, Welch, Grandgenett, Wu, & Nelson, 2015). The burgeoning international interest in science, technology, engineering, and mathematics (STEM) spurred on by business and policy leaders has forged a strong connection into and influence on schooling. Many countries, as seen in their national policies and reports, have invested and promoted STEM as a pillar of secondary education. A report published in the United Kingdom (UK) identified STEM education as being central to their workforce development and key in the reduction of economic problems (National Audit Office, 2018). As a result, the UK now has a National STEM Education network with the goal of securing STEM education for all young people. In the United States (US), policymakers and stakeholders have argued for the expansion and improvement of STEM education as a critical component to developing and maintaining the nation's capacity for innovation (National Science and Technology Conference, 2018). The urgency to advance STEM is also evident in calls from the Office of the Chief Scientist (2014) and other groups and organizations concerned with Australia's status as a leader in education and having a substantive position in world economics and sustainability. The report from Australia identified a STEM workforce with critical thinking and problem-solving skills as pertinent to driving its economic prosperity and fostering creativity and innovative ideas (Timms, Moyle, Weldon, & Mitchell, 2018). Other countries such as Malaysia, Canada, Turkey, China, and nations in the European Union (EU) have instituted a range of policies to support the development of STEM education in their secondary schools (Freeman, Marginson, & Tytler, 2014). This international and heightened attention to secondary STEM education is a direct response to the need for an informed and literate citizenry and a continued supply of a workforce prepared with 21st-century skills to respond to global and economic challenges.

Secondary school experiences prepare students for post-secondary pathways that may include essential prerequisites to career technical training, advanced college and graduate studies, and technical skills for the workplace. For the purposes of this chapter, secondary education is defined as the period of formal schooling from grade 6 until the end of the secondary program. Globally, notable differences and trends exist across secondary grade level bands; specifically, lower secondary refers to grades 6–8, and "high schools" being from grade 9, with overlap in some places. Some students may choose to continue the study of STEM-related disciplines in post-secondary institutions. For others not pursuing such fields and who may enter vocational training, an effective STEM program in secondary education could foster the development of STEM literacy and 21st-century skills.

As noted in policy documents, these skills and competencies are important for the workplaces including the manufacturing industries.

A review of educational reforms and the enactment of STEM-focused curricula has revealed a range of initiatives and models. For example, in the US, documents such as the New Science Framework (NRC, 2012), Next Generation Science Standards (NGSS Lead States, 2013) and the Common Core Science Standards (CCSS) (National Governors Association, 2010) emphasize the importance of an interdisciplinary approach to STEM teaching and learning and call for incorporating contexts that reveal real-world issues. Furthermore, performance expectations outlined in the NGSS (NGSS Lead States, 2013) related to secondary education call for the development of knowledge across disciplines; demonstration of proficiencies in mathematical thinking; and obtaining, evaluating, and communicating information. These salient practices, when appropriately developed, support the achievement of STEM literacy described as the integration of the STEM disciplines and the tools and knowledge necessary to solve complex issues (Balka, 2011; Mohr-Schroeder, Bush, & Jackson, 2018). Australia, facing the challenge of a "crowded traditional curriculum," introduced the Australia Curriculum: Technologies focusing on systems thinking as a unifying approach and with intent that students from foundation to year eight in schools develop levels of proficiencies in design and digital technologies (Timms et al., 2018). In Korea, as reported by Freeman, Marginson, and Tytler (2015), the development of a STEM curriculum is driven by the relevance of science and technology in daily life and the public interests in new discoveries and awareness.

Secondary STEM education can be considered a single or multidisciplinary field (Holmlund, Lessig, & Slavit, 2018), but there seems to be a lack of consensus among educational stakeholders concerning its conceptualizations and approaches. Scholars embrace the notion that an interdisciplinary approach can foster students' STEM identity (Holmegaard, Madsen, & Ulriksen, 2014; Gonsalves, Silfver, Danielsson, & Berge, 2019), develop 21st-century workforce skills (Kennedy & Odell, 2014), and lead to well-rounded, scientifically literate global citizens (Bybee, 2013). In this chapter, we examine STEM learning in secondary schools and discuss the approaches, and challenges of integrating two or more disciplines. In addition, we highlight the personal and global economic benefits of secondary STEM education. Our discussion ends with a proposal for a research agenda that will secure the reduction of ambiguity in STEM education and from which will emerge a global cohesive vision as indicated in international policies along with strategies and best practices to support its continued enactment.

Current Landscape: STEM in Secondary Education

While goals for STEM education have been identified at the national levels and expressed in policy documents (Bybee, 2013; Kennedy & Odell, 2014), there is no agreed-upon national or international approach to curricular design for secondary education. Such decisions are usually left to school administrators and teachers (McNally, 2012; Roehrig, Moore, Wang, & Park, 2012). As a result, STEM in secondary education exists within a vast landscape of variability integrating two or more disciplines within the context of existing curricular frameworks (Moore, Johnson, Peters-Burton, & Guzey, 2016), as a program (Bicer & Capraro, 2018; Wiswall, Stiefel, Schwartz, & Boccardo, 2014), or as specialized courses of studies within schools classified as STEM schools (LaForce et al., 2016; Wiswall et al., 2014; Subotnik, Tai, Rickoff, & Almarode, 2009). This variability does not, however, detract from the general agreement that STEM within secondary education should involve all students in a rigorous curriculum, be applicable to real-world experiences, and include problem or project-based learning opportunities that contribute to the building of 21st-century skills (Bybee, 2013; Peters-Burton, Lynch, Behrend, & Means, 2014). In the report on STEM education in the US, *Charting a Course for Success: America's Strategy for STEM Education* (NSTC, 2018), the federal government identified three aspirational goals for the achievement of a high-quality STEM education:

(1) build strong foundations for STEM literacy, (2) increase diversity, equity, and inclusion in STEM, and (3) prepare the STEM workforce for the future. These goals confirm the importance of quality STEM education for all learners (particularly those who historically have been underserved and underrepresented), while also acknowledging that the nation's economic welfare is dependent upon increasing access and inclusivity in STEM education.

In secondary STEM education, combinations of the disciplines are taught within existing traditional school curricula as concepts or practices providing support or deepening learning in the core or host subject (Kelley, & Knowles, 2016; Asghar, Ellington, Rice, Johnson, & Prime, 2012). Described as "ad hoc infusion" (Katehi, Pearson, & Feder, 2009), these STEM-oriented curricula embed disciplinary processes and competencies such as problem solving, creativity, and critical thinking skills into a core subject. These pertinent skills and disciplinary content knowledge in secondary STEM education have been lauded as being instrumental in fostering and contributing to the development of functional citizens and ensuring the continued pipeline toward higher-level studies including research, mathematics, science, and engineering (Archer et al., 2012; Capraro & Nite, 2014).

Science and Engineering

Engineering concepts and skills and the alignment with science content standards, though not a novel idea (Grubb & Strimel, 2015), have been given much credence in increasing the pipeline with a talented workforce, capable of innovation and prepared to solve real-world problems through design, troubleshooting, and analysis activities (Brophy, Klein, Portsmore, & Rogers, 2008; Bybee, 2010; Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006; Chien & Chu, 2018; Grubb & Strimel, 2015). Globally, engineering design and practices are emerging as dynamic elements of science education. For example, in the Netherlands as well as in many other countries, there is increasing interest in integrating engineering as part of the general education (Kőycű & de Vries, 2016). In Malaysia, attempts at integration include the introduction of biotechnology into science curriculum (Yasin, Amin, & Hin, 2018). In the US, the New Science Framework (NRC, 2012) explicitly incorporates engineering practices, raising them to the same level as science practices within the three-dimensional approach to science learning. The three dimensions to science learning (NRC, 2012) include core science ideas, crosscutting concepts, and science and engineering practices.

Science investigation and engineering design together provide a structure in which students participate in science as a social enterprise and connect disciplinary concepts and principles to their own experiences and ideas (NSTC, 2018). While science usually serves as the host discipline with engineering-based problem solving (Goonatilake & Bachnak, 2012; Chien & Chu, 2018), research indicates that in such integration, engineering has the potential to occupy more than a "spectator" role. Engineering design, emphasis on problem solving and optimizing solutions using a variety of tools for modeling and analysis are integral to students' preparation for engaging in systematic processes to solve societal and environmental challenges (Brophy et al., 2008; Grubb & Strimel, 2015; NGSS Lead States, 2013). In a study examining the effects of engineering design-focused modules on student learning in lower secondary school science, Cantrell et al. (2006) concluded that engineering design experiences facilitated the development of science content knowledge and higher-order thinking skills such as analysis and synthesis. Their results also indicated that a curriculum that includes engineering design-based activities and in which students seek solutions to authentic real-world issues may reduce academic achievement gaps among underrepresented populations of learners.

Reports from integrating engineering into secondary education curricula reveal mixed results. In Mooney's and Laubach's (2002) Adventure Engineering program, students immersed in open-ended design experiences improved in achievement in mathematics and science but showed no significant change in knowledge about engineering (Mooney & Laubach, 2002). In another project, engineering was purposively integrated into science to enrich the regular school curricula including expanded opportunities for creativity and problem solving (Redmond, Thomas, High, Scott, Jordan, & Dockers, 2011). This program resulted in a significant impact on students' confidence, awareness of engineering, and interest in engineering as a potential career. Other work exploring the impact of integrating an engineering design-based science unit reported statistically significant achievement for life science among a group of special education students (Guzey, Moore, Harwell, & Moreno, 2016). Even with mixed results, an integrated science and engineering curriculum provides a rich context for bridging classroom lessons to real-world experiences, allowing students to develop knowledge and abilities necessary for fostering innovation and piquing their curiosity and motivation toward both disciplines (Brophy et al., 2008; Grubb & Strimel, 2015).

Using Technology as the Lens to Inform STEM

Technological advances have permeated many areas of life in the 21st century, thus igniting an even greater interest in pursuing the STEM enterprise as a field of study. In support of the global consensus that technology integration holds great promise for enhancing STEM learning, educators are now capitalizing on its potential to motivate students by connecting learning to digital cultures characteristic of real-world perspectives (Saavedra & Opfer, 2012; Basu et al., 2016; Dogan & Robin, 2015). For example, a study examining the impact of online forensic science games on secondary students' knowledge, attitudes, and science careers, Miller (2011) offered evidence to support the positive role of technology in knowledge acquisition, its motivational effects on learners, and its use as a means to foster the development of 21st-century skills. Upper-level secondary students in Malaysia experienced the positive impact of technology through a biotechnology-infused classroom that allowed them to apply and manipulate biological processes (Yasin et al., 2018). The researchers found that even though teachers were limited in their preparation to teach the subject, access to appropriate technologies, resources and simulations, and ease of communication impacted their teaching and facilitated students' learning.

Europe and the US have a long history of integrating technology into their formal school curricula, and this has expanded to other countries. In recent international reports, STEM integration has now become a central issue in educational reform in countries like Israel where digital technologies in science classes exist as both an instructional tool and a separate discipline with its own parameters (Valkanova & Watts, 2007). Emphasis on the incorporation of technology-rich STEM-based programs with secondary students has demonstrated how technological tools and methods have been used to foster collaborative learning environments and enhance student ownership and independence (Ardito, 2010; Clayton & Ardito, 2009; Ardito, Mosley, & Scollins, 2014; Capraro & Jones, 2013; Yasin et al., 2018). In other efforts, technology integration in STEM learning has impacted secondary learners' effectiveness, attitudes, and creativity (Lou, Chung, Dzan, Tseng, & Shih, 2013); achievement, and self-efficacy (Liu, Cho, & Schallert, 2006; Ketelhut, 2007); and student-directed scientific inquiry in real-world settings by improving their problem-solving abilities (Barak & Dori, 2005).

As technology becomes more indispensable, computer and network technologies are now contributing to experiential learning in STEM. In addition to computer science curricula and the integration of computational thinking skills, there is now much support for the inclusion of robotics as a viable platform for the application of STEM (Allen, 2013; Barak & Assal, 2018; Rihtarsic, Avsec, & Kocijancic, 2016). For example, Bowen, DeLuca, and Franzen (2016), in their study of content knowledge learning in a computer simulation modeling program, posited that students with less content knowledge can achieve certain goals if sufficiently engaged in simulation. Their findings also raise the issue of the extent to which students integrate content knowledge, procedural knowledge, experimental knowledge, and trial and error to achieve learning outcomes. While the interdisciplinary nature of computer simulation modeling raises questions about the nature and quality of content knowledge, it provides a unique opportunity for students to persevere through challenges and offers a platform from which the vision of STEM can be realized in secondary classrooms.

Science and Mathematics

When students learn mathematics and science simultaneously as in integration, they are likely to increase comprehension in both subjects, and the experiences could provide the intellectual excitement necessary to increase interest and engagement (Weinberg, & Sample McMeeking, 2017; Schroeder, Scott, Tolson, Huang, & Lee, 2007). Researchers in the fields of both mathematics education and science education have long asserted that the two disciplines are complementary (Lee, Chauvot, Plankis, Vowell, & Culpepper, 2011; Boboňová, Čeretková, Tirpáková, & Markechová, 2019; Schroeder et al., 2007). However, while some educators have lauded the usefulness of the mathematics-science integration (Becker & Park, 2011), others have indicated that the nature and level of learning appear to differ for the two disciplines and is less evident for mathematical outcomes (Shaughnessy, 2013; Boboňová et al., 2019).

In supporting the integration of mathematics and science, Treacy and O'Donoghue (2014) describe mathematics as a universal tool for evaluating a set of values in addition to modeling skills necessary for quantitative analysis of large data sets prevalent in science. The expression of the quantitative results can therefore lead to the discovery of new patterns or relationships (Michaels, Shouse, & Schweingruber, 2008). Mathematics and science integration allow students to learn organized knowledge structures drawn from both disciplines, explore the interconnectedness of the disciplines and heighten their understanding of the relevance and real-life applications of each discipline (Enderson, 2015; Huntley, 1998; McHugh, Kelly, & Burghardt, 2017).

An examination of existing models of integration shows a greater focus on science, with mathematics content integration that gives little regard to learning the discipline (Boboňová et al., 2019). They contend that simply adding mathematical concepts in science instruction is not necessarily supportive in providing a meaningful context for developing an understanding of mathematical principles. This observation has generated debates as educators invoke the call for mathematics to be made transparent and explicit and to occur within the context of a problem that requires significant mathematical skills (Shaughnessy, 2013; Weinberg & Sample McMeeking, 2017). Accordingly, the context of the problem should explicitly draw from both disciplines and be taught in a manner consistent with inquiry-based pedagogical strategies. Ideally in these strategies, the abstract concepts in mathematics are realized as students develop and use skills such as measurement and graphing in interpreting data which then become reinforced across the two disciplines. Stinson, Harkness, Meyer, and Stallworth (2009) also note that the ability to apply mathematics within a real-world context is at the core of quantitative reasoning where, as a universal language, mathematics provides scientists with another system for sharing, communicating, and understanding science concepts.

While many countries subscribe to a discipline-centered curriculum, over the last decade places like Slovakia have seen the rise of interdisciplinary curriculum in which mathematics is integrated into specific science disciplines such as the life sciences. This move toward mathematics integration according to Boboňová et al. (2019) has emerged in response to the need to improve overall quantitative skills required in secondary and post-secondary science learning. In the current reforms in the US, both the NGSS (NGSS Lead States, 2013) and the Common Core State Standards (CCSS, 2010) have affirmed the importance of integrating science and mathematics and the role each discipline plays in providing a context in which students can make connections across the two disciplines. Both US standards are grounded in the belief that the systematic inclusion of mathematics and science in instruction can satisfy the learning of important disciplinary concepts and skills as indicated in the respective curricular documents. The general consensus among educators is that science and mathematics integration will allow for improvement in the complexity and scope of student knowledge and comprehension (Treacy & O'Donoghue, 2014). However, at the heart of the debates around the integration is the need for a common understanding of how to utilize mathematical approaches while simultaneously employing scientific examples.

STEM Curriculum: Programmatic Approach

A promising approach to enacting STEM integration in secondary education has been the development of a cohesive course of studies in which learning is anchored in meaningful contexts. Project Lead the Way (PLTW, 2019) is one such program. This premier engineering education program in the US provides a STEM-focused curriculum that concentrates on the integration of engineering with science and mathematics within the context of real-world challenges. The program was developed in response to concerns over the diminishing number of students in the US choosing to enter science and engineering post-secondary education programs. PLTW specifically addresses the anticipated needs of the 21st-century workforce and provides students with a foundation and a pathway to college and careers in STEM-related fields. The sequence of engineering courses in PLTW encourages students to use their mathematics and science knowledge and skills to complete problems applicable to their everyday lives.

Research examining the effectiveness of PLTW on student science achievement has garnered some mixed results. PLTW in general has contributed to positive academic achievement on standardized measures and motivation in science and engineering (Tai, 2012). Additionally, studies have determined the significance of PLTW and its hands-on, project-based engineering curriculum as students demonstrated higher scores on state mathematics assessments, a higher percentage met the college-ready criterion, a higher percentage enrolled in higher education institutions, and non-college-bound PLTW students earned higher wages (Van Overschelde, 2013). Other studies, however, did not find significant differences when examining students' achievement in mathematics (Tran & Nathan, 2010). The discrepancies in the findings indicate the complex challenges engineering education programs like PLTW face as they seek to effectively integrate the disciplines in STEM in ways that support the construction of academic content and the development of the skills to a wide range of students.

Like PLTW, another approach to STEM integration and given much credit in the literature is STEM project based learning (PBL). As a pedagogical strategy, STEM PBL (Abbott, 2016; Capraro & Nite, 2014) offers a comprehensive and interdisciplinary approach to investigating authentic problems from which students develop critical thinking skills and values along with specific content knowledge. A hallmark of STEM PBL is its focus on learning in the context of real-world challenges that require developing and using skills, tools, and knowledge central to the disciplines. When PBL is carefully designed with attention to the content knowledge of each discipline and enacted accordingly, studies show increased academic achievement, student engagement, interest in pursuing STEM careers, and overall positive attitudes towards STEM (Newman, Dantzler, & Coleman, 2015; Guzey et al., 2016; Dorph, Bathgate, Schunn, & Cannady, 2018). Ideally the integration of a well-developed STEM PBL curriculum allows secondary students to experience the overlapping nature of disciplines leading to deep conceptual understanding.

Students engaged in STEM PBL confront global and local challenges as they master grade-level content knowledge and skills and habits of mind necessary for success (Abbott, 2016; Capraro & Jones, 2013; Korur, Efe, Erdogan, & Tunc, 2017; Newman et al., 2015). Due to its wide reach and authenticity in engaging learners, educators note the extent to which PBL curriculum seamlessly cuts across traditional content lines and integrates engineering and technological design, inquiry-based science, and mathematical reasoning in the process of developing a potential curricular prototype for the future (Johnson, Peters-Burton, & Moore, 2016). Students placed at the center of the learning process become motivated (Flores, 2018), and the emerging knowledge, both meaningful and relevant, can impact their academic choices as they contemplate high school studies and beyond. A well-designed PBL STEM curriculum according to Knezek, Christensen, Tyler-Wood, and Periathiruvadi (2013) can therefore be very effective during the secondary years of schooling. Other scholars have cited increases in science academic achievement (Newman et al., 2015) changes in attitudes (Guzey et al., 2016; Dorph et al., 2018), and positive impacts on the learning and engagement of students from underrepresented populations (Flores, 2018).

Another program, *STEM Road Map: A Framework for Integrated STEM Education*, is described by the editors, Johnson et al. (2016), as "a coordinated response to the need for addressing STEM learning in K-12" (p. 4). The program embraces the reform efforts presented by the new framework, NGSS, and the US national standards expressed in the common core. Organized around five real-world STEM themes—cause and effect, innovation and progress, the represented world, sustainable systems, and optimizing the human experience—the curriculum framework is spiraled and reinforced throughout the K-12 environment. One of the important features of the STEM Road Map is the ease of implementation supported by the authentic and facilitative learning environments in which students engage in real-world STEM projects (Johnson et al., 2016). Other unique features of the STEM Road Map framework include the distinctive roles for all the content areas; teachers working collaboratively across disciplines to implement the integrated curriculum; and students being immersed in authentic, project- and problem-based learning across traditional content areas, integrating technology, engineering, scientific inquiry, and mathematical reasoning. The learning experiences being personal, relevant and of interest to secondary students serve the multiple purposes of supporting the development of 21st-century competencies, STEM literacy, and laying the foundation for career choices that will secure a pipeline of STEM experts and innovators.

In addition to increasing STEM curricular developments, there has also been a growing number of STEM-focused schools (Scott, 2012). STEM-focused secondary schools are classified into three categories by the National Research Council (2012): selective, inclusive, or career and technical education (CTE) focused. Studies on STEM- focused schools and non-STEM focused schools have not shown significant differences in academic achievement, based on standardized test results (Bicer & Capraro, 2018; Wiswall et al., 2014). However, studies do indicate STEM-focused schools lessen the achievement gap between underrepresented student populations and their White counterparts (Bicer & Capraro, 2018; Wiswall et al., 2014). As summarized by Wiswall et al. (2014), for average students, the effects of attending a STEM high school are not significant, but STEM-focused schools have the potential to be a powerful tool for leveling the playing field among varying populations of learners and to mitigate student outflows into STEM.

Challenges to STEM Integration in Secondary Education

STEM learning in secondary education holds the undeniable promise of impacting the educational trajectory of learners as they graduate high school, yet there are many challenges to its enactment. Some of these challenges include the ambiguity of the meaning and interpretation of STEM and the lack of a consistent operational definition; teachers' preparedness to teach the principles, knowledge, and practices across the disciplines; access to a viable curriculum and related materials; and already crowded programs of studies that in many cases are tightly knitted to historical norms, procedures, and structures. Despite the crafting of the STEM acronym in the 1990s, and the dramatic momentum in the enterprise over the years (Asghar et al., 2012), there remains a pronounced lack of consensus on its meaning within the context of educational policies, programs, and curricular practices (Bybee, 2013; Sanders, 2009). This ambiguity in meaning diminishes the power of STEM as the conversations around goals and expectations project out from the national policies and translated into curricular practices (Sanders, 2009).

Teachers prepared to teach traditional single courses offer one of the main challenges to STEM integration (Stohlmann, Moore, McClelland, & Roehrig, 2011). This is compounded by the lack of an established STEM curriculum. While teachers will require learning opportunities in multiple disciplinary content knowledge and STEM-related pedagogies, some researchers responding to the lack of knowledge suggest that teachers could adopt new ways of collaborating and co-teaching to offset the existing deficit in content knowledge (Roehrig et al., 2012; Capraro & Nite, 2014; McNally, 2012). Embracing STEM learning in secondary education requires a shift in teachers' professional development along with significant implications for teacher preparation programs.

Curricular materials that purposefully identify and connect relevant practices and specific disciplinary knowledge are essential to support STEM education in secondary schools (Katehi et al., 2009; Rihtarsic et al., 2016). In addition, the curriculum should be responsive to the learning needs of historically underrepresented students in STEM disciplines, including students who are female, have low socioeconomic status (SES), and who represent certain ethnic minorities and indigenous groups. The curriculum should be culturally responsive, leveraging students' funds of knowledge (Ladson-Billings, 2014; Paris, 2012), and provide equitable access to each of the disciplines, thus holding the promise of broadening participation. Issues related to the curriculum also include the impact of high-stakes assessment, as what is tested dictates the value and attention ascribed to teaching. Furthermore, current structural organization of schools, access to viable curriculum and materials, and approaches to pedagogical practices offer challenges to the enactment of sustainable STEM programs for secondary education (Katehi et al., 2009) including attention to the organization of grade levels, teachers' assignments, and assessment policies. Moving forward, the continued evolution of STEM learning in secondary schools will require a curriculum with clear delineation of the disciplinary content knowledge and or specialized skills and dispositions from each of the four component disciplines—science, technology, engineering, and mathematics.

Looking Forward: A Research Agenda for the 21st Century

STEM learning in secondary education is important to increase students' achievement in science and mathematics, improve STEM literacy, and foster the development of skilled 21st-century workers and innovators to advance areas within STEM fields (Stohlmann et al., 2011; Navracsics, 2017; NRC, 2012; NSTC, 2018). The literature is replete with claims of the effectiveness of STEM learning that have emerged from pockets of research activities which, from our observation and consistent with those of other scholars, is lacking in substantive empirical evidence. To provide guidance going forward, what is needed is a definitive model of STEM education including its progression and articulation across K-12 schooling, and the extent to which it supports meaningful learning across all four disciplines. STEM education in secondary schools could be better informed by a universally accepted curricular framework that could be imported into traditional school structures. This framework would include best practices, relevant and appropriate assessments, and would be complemented with the preparation of a cadre of competent and dedicated STEM teachers and supportive school administrators. From our examination of the landscape of STEM education in secondary education, we propose a research agenda that includes unearthing and learning from the past and preparing for the future.

Despite the pockets of positive results highlighting the development of STEM-related interest and identity and the potential to foster learning across the four disciplines, there is a paucity of information on best strategies and approaches to inform classroom practices. This is further complicated by the many different approaches to STEM, each with its own implementation challenges and variant outcomes. We are therefore at a time in the history of STEM education that warrants a well-developed systematic analysis of the research that has occurred over the past nineteen or so years, and a mixed-methods longitudinal study to investigate trends in processes and practices. The proposed studies would be twofold. First, the systematic review would provide insights into past occurrences and would reveal possible questions and hypotheses to direct future research efforts. Perhaps most importantly, the systematic review would provide information to guide the development of a consistent operational definition of STEM. Second, the longitudinal study would respond to questions related to the impact of STEM education in secondary schools on students' choice of subjects and career trajectory. Furthermore, the findings could inform the refinement of models of best practices, including learning goals in the context of the individual subjects and across the four disciplines. Thus ending the concerns as to what should be contained in a STEM program in secondary education.

Conclusion

In the review of STEM education in secondary schools, the consensus is that an integrated approach has the potential to facilitate students' development of the necessary skills, knowledge, and dispositions to be functional 21st-century citizens. Furthermore, an integrated STEM education that provides real-world, relevant, and appropriate learning experiences can prepare students with college-readiness skills, increase the number and diversity pursuing a career in a STEM-related field, and provide a continuous supply of skilled and innovative workers necessary to maintain worldwide economic stability. Advocates for STEM education in secondary education (Krapp & Prenzel, 2011; Stohlmann et al., 2011) contend that teaching in ways that allow students to make connections to real-world issues and challenges can make the disciplines more relevant and improve academic achievement and students' interest. The successful achievement of the promise of STEM education in secondary schools hinges on the development of a cohesive definition, creation of real-world curricular materials, comprehensive STEM teacher preparation, and the alignment of secondary school practices with international goals for STEM education. Ultimately, increasing the access to and the quality of STEM education in secondary schools will foster creativity and ensure innovative solutions to current and future global dilemmas.

References

Abbott, A. (2016). Chemical connections: A problem-based learning, STEM experience. *Science Scope, 39*(7).

Allen, K. C. (2013). Robots bring math-powered ideas to life. *Mathematic Teaching in the Middle School, 18*(6), 340–347.

Archer, L., DeWitt, J., Osborne, J., Dillon, J., Willis, B., & Wong, B. (2012). Science aspirations, capital, and family habitus: How families shape children's engagement and identification with science. *American Educational Research Journal, 49*(5), 881–908.

Ardito, G. (2010). *The shape of disruption: XO laptops in the fifth-grade classroom*. White Plains, NY: Pace University.

Ardito, G., Mosley, P., & Scollins, L. (2014). WE, ROBOT: Using robotics to promote collaborative and mathematics learning in a middle school classroom. *Middle Grades Research Journal, 9*(3), 73–88.

Asghar, A., Ellington, R., Rice, E., Johnson, F., & Prime, G. M. (2012). Supporting STEM education in secondary science contexts. *Interdisciplinary Journal of Problem-Based Learning, 6*(2), 85–125.

Balka, D. (2011). Standards of mathematical practice and STEM. Stillwater, OK. *Math-science Connector Newsletter,* 6–8.

Barak, M., & Assal, M. (2018). Robotics and STEM learning: Students' achievements in assignments according to the P3 task taxonomy—practice, problem solving, and projects. *International Journal of Technology and Design Education*, (1), 121–144.

Barak, M., & Dori, Y. J. (2005). Enhancing undergraduate students' chemistry understanding through project-based learning in an IT environment. *Science Education, 89*(1), 117–139.

Basu, S., Biswas, G., Sengupta, P., Dickes, A., Clark, D., & Kinnebrew, J. (2016). Identifying middle school students' challenges in computational thinking-based science learning. *Research & Practice in Technology Enhanced Learning, 11*(1), 1–35.

Becker, K., & Park, K. (2011). Effects of integrative approaches among science, technology, engineering, and mathematics (STEM) subjects on students' learning: A preliminary meta-analysis. *Journal of STEM Education: Innovations & Research, 12*, 23–36.

Bicer, A., Capraro, R. M., & Capraro, M. M. (2018). Hispanic students' mathematics achievement in the context of their high school types as STEM and non-STEM schools. *International Journal of Mathematical Education in Science and Technology*, *49*(5), 705–720.

Boboňová, I., Čeretková, S., Tirpáková, A., & Markechová, D. (2019). Inclusion of interdisciplinary approach in the mathematics education of biology trainee teachers in Slovakia. In *Interdisciplinary mathematics education* (pp. 263–280). Cham, Switzerland: Springer.

Bowen, B. D., DeLuca, V. W., & Franzen, M. M. S. (2016). Measuring how the degree of content knowledge determines performance outcomes in an engineering design-based simulation environment for middle school students. *Computers & Education*, *117*.

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

Bybee, R. W. (2013). *The case for STEM education: Challenges and opportunities*. Arlington, VA: National Science Teachers Association Press.

Cantrell, P., Pekcan, G., Itani, A., & Velasquez-Bryant, N. (2006). The effects of engineering modules on student learning in middle school science classrooms. *Journal of Engineering Education, 95*(4), 301–309.

Capraro, M. M., & Jones, M. (2013). Interdisciplinary stem project-based learning. In R. M. Capraro, M. M. Capraro, & J. Morgan (Eds.), *Project-based learning: An integrated science, technology, engineering, and mathematics (STEM) approach* (2nd ed., pp. 47–54). Rotterdam, The Netherlands: Sense.

Capraro, M. M., & Nite, S. B. (2014). Stem integration in mathematics standards. *Middle Grades Research Journal, 9*(3), 1.

Chien, Y. H., & Chu, P. Y. (2018). The different learning outcomes of high school and college students on a 3D-printing STEAM engineering design curriculum. *International Journal of Science and Mathematics Education*, *16*(6), 1047–1064.

Clayton, C., & Ardito, G. (2009). Teaching for ownership in the middle school science classroom: Towards practical inquiry in an age of accountability. *Middle Grades Research Journal*, *4*(4), 53–79.

Common Core State Standards Initiative. (2010). *Common Core State Standards for mathematics*. Retrieved from http://www.corestandards.org

Dogan, B., & Robin, B. (2015). Technology's role in STEM education and the stem S.O.S. Model. In Sahin, A. (Ed.D.), *A practice-based model of STEM teaching: STEM students on the stage (SOS)* (pp. 77–94). Rotterdam, The Netherlands: Sense Publishing.

Dorph, R., Bathgate, M. E., Schunn, C. D., & Cannady, M. A. (2018). When I grow up: The relationship of "science learning activation" to STEM career preferences. *International Journal of Science Education, 40*(9), 1034–1057.

Enderson, M. C. (2015). Ready, aim, fire your cannons! *Teaching Children Mathematics, 21*(8), 502–506.

Flores, C. (2018). Problem-based science, a constructionist approach to science literacy in middle school. *International Journal of Child-Computer Interaction*, *16*, 25–30.

Freeman, B., Marginson, S., & Tytler, R. (2015). *The age of STEM: Educational policy and practice across the world in Science, Technology, Engineering and Mathematics*. London: Routledge, Taylor & Francis.

Gonsalves, A. J., Silfver, E., Danielsson, A., & Berge, M. (2019). "It's not my dream, actually": Students' identity work across figured worlds of construction engineering in Sweden. *International Journal of STEM Education*, *6*(1), 1–17.

Goonatilake, R., & Bachnak, R. A. (2012). Promoting engineering education among high school and middle school students. *Journal of STEM Education: Innovations & Research*, *13*(1), 15–21.

Grubbs, M., & Strimel, G. (2015). Engineering design: The great integrator. *Journal of STEM Teacher Education*, *50*(1), 77–90.

Guzey, S. S., Moore, T. J., Harwell, M., & Moreno, M. (2016). STEM integration in middle school life science: Student learning and attitudes. *Journal of Science Education and Technology*, *25*(4), 550–560.

Holmegaard, H. T., Madsen, L. M., & Ulriksen, L. (2014). To choose or not to choose science: Constructions of desirable identities among young people considering a STEM higher education programme. *International Journal of Science Education*, *36*(2), 186–215.

Holmlund, T., Lessig, K., & Slavit, D. (2018). Making sense of "STEM education" in K-12 contexts. *International Journal of STEM Education*, *5*(32), 1–18.

Huntley, M. (1998). *Design and implementation of a framework for defining integrated mathematics and science education*. Hoboken: Blackwell Publishing Ltd.

Johnson, C., Peters-Burton, E., & Moore, T. (Eds.). (2016). *STEM road map: A framework for integrated STEM education*. New York, NY: Routledge.

Katehi, L., Pearson, G., & Feder, M. (2009). The status and nature of K-12 engineering education in the United States. *The Bridge*, *39*(3), 5–10.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1), 11.

Kennedy, T. J., & Odell, M. R. L. (2014). Engaging students in STEM education. *Science Education International*, *25*(3), 246–258.

Ketelhut, D. J. (2007). The impact of student self-efficacy on scientific inquiry skills: An exploratory investigation in River City, a multi-user virtual environment. *Journal of Science Education and Technology, 16*(1), 99–111.

Knezek, G., Christensen, R., Tyler-Wood, T., & Periathiruvadi, S. (2013). Impact of environmental power monitoring on middle school student perceptions of STEM. *Science Education International*, *24*(1), 98–123.

Korur, F., Efe, G., Erdogan, F., & Tunç, B. (2017). Effects of toy crane design-based learning on simple machines. *International Journal of Science and Mathematics Education*, *15*(2), 251–271.

Kőycű, Ü., & de Vries, M. J. (2016). What preconceptions and attitudes about engineering are prevalent amongst upper secondary school pupils? An international study. *International Journal of Technology and Design Education*, *26*(2), 243–258.

Krapp, A., & Prenzel, M. (2011). Research on interest in science: Theories, methods, and findings. *International Journal of Science Education*, *33*(1), 27–50.

Ladson-Billings, G. (2014). Culturally relevant pedagogy 2.0: Aka the remix. *Harvard Educational Review*, *84*(1), 74–84.

LaForce, M., Noble, E., King, H., Century, J., Blackwell, C., Holt, S., . . . Loo, S. (2016). The eight essential elements of inclusive STEM high schools. *International Journal of STEM Education, 3*(21), 1–11. doi:10.1186/s40594-016-0054-z.

Lee, M. M., Chauvot, J., Plankis, B., Vowell, J., & Culpepper, S. (2011). Integrating to learn and learning to integrate: A case study of an online master's program on science–mathematics integration for middle school teachers. *The Internet and Higher Education*, *14*(3), 191–200.

Liu, M., Cho, Y., & Schallert, D. (2006). Middle school students' self-efficacy, attitudes, and achievement in a computer-enhanced problem-based learning environment. *Journal of Interactive Learning Research, 17*(3), 225–242.

Lou, S., Chung, C., Dzan, W., Tseng, K., & Shih, R. (2013). Effect of using TRIZ creative learning to build a pneumatic propeller ship with applying STEM knowledge. *International Journal of Engineering Education, 29*(2), 365–379.

McHugh, L., Kelly, A. M., & Burghardt, M. D. (2017). Teaching thermal energy concepts in a middle school mathematics-infused science curriculum. *Science Scop*e, *41*(1), 43.

McNally, T. (2012). Innovative teaching and technology in the service of science: Recruiting the next generation of STEM students. *Journal of the Scholarship of Teaching and Learning*, *12*(1).

Michaels, S., Shouse, A. W., & Schweingruber, H. A. (2008). *Ready, set, science!: Putting research to work in K-8 science classrooms*. Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: National Academies Press.

Miller, L., Chang, C., Wang, S., Beir, M., & Klisch, Y. (2011). Learning and motivational impacts of a multimedia science game. *Computers and Education*, *57*, 1425–1433.

Mohr-Schroeder, M., Bush, S. B., & Jackson, C. (2018). K12 STEM education: Why does it matter and where are we now? *Teachers College Record*. Retrieved February 3, 2018, from http://www.tcrecord.org ID Number: 22288.

Mooney, M. A., & Laubach, T. A. (2002). Adventure engineering: A design centered, inquiry-based approach to middle grade science and mathematics education. *Journal of Engineering Education, 91*(3), 309–318.

Moore, T. J., Johnson, C. C., Peters-Burton, E. E., & Guzey, S. S. (2016). The need for a STEM road map. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), *Stem road map: A framework for integrated STEM education*. New York, NY: Routledge.

National Audit Office. (2018). *Delivering STEM (science, technology, engineering and mathematics) skills for the economy*. Victoria and London: National Audit Press Office.

National Governors Association. (2010). *Common core state standards*. Washington, DC: Author.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

National Science and Technology Council. (2018). *Charting a course for success: America's strategy for STEM education: A report by the Committee on STEM Education of the National Science and Technology Council*. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf

Navracsics, T. (2017). *Why STEM subjects and democratic citizenship go together.* Retrieved from https://ec.europa.eu/commission/commissioners/2014-2019/navracsics/announcements/why-stem-subjects-and-democratic-citizenship-go-together_en

Newman, J. L., Dantzler, J., & Coleman, A. N. (2015). Science in action: How middle school students are changing their world through STEM service-learning projects. *Theory into Practice, 54*(1), 47–54.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Nugent, G., Barker, B., Welch, G., Grandgenett, N., Wu, C., & Nelson, C. (2015). A model of factors contributing to STEM learning and career orientation. *International Journal of Science Education, 37*(7), 1067.

Office of the Chief Scientist. (2014). *Science, technology, engineering and mathematics: Australia's future*. Canberra: Australian Government.

Ogle, J. P., Hyllegard, K. H., Rambo-Hernandez, K., & Park, J. (2017). Building middle school girls' self-efficacy, knowledge, and interest in math and science through the integration of fashion and STEM. *Journal of Family & Consumer Sciences*, *109*(4), 33.

Paris, D. (2012). Culturally sustaining pedagogy: A needed change in stance, terminology, and practice. *Educational Researcher*, *41*(3), 93–97.

Peters-Burton, E., Lynch, S. J., Behrend, T. S., & Means, B. B. (2014). Inclusive STEM high school design: 10 critical components. *Theory into Practice*, (1), 64.

Project Lead the Way. (2019). *PLTW, state by state*. Retrieved from https://www.pltw.org/about-us/pltw-state-presence.

Redmond, A., Thomas, J., High, K., Scott, M., Jordan, P., & Dockers, J. (2011). Enriching science and math through engineering. *School Science and Mathematics*, *111*(8), 399–408.

Rihtarsic, D., Avsec, S., & Kocijancic, S. (2016). Experiential learning of electronics subject matter in middle school robotics courses. *International Journal of Technology and Design Education*, (2), 205.

Roehrig, G. H., Moore, T. J., Wang, H., & Park, M. S. (2012). Is adding the E enough? investigating the impact of K-12 engineering standards on the implementation of STEM integration. *School Science and Mathematics, 112*(1), 31–44.

Saavedra, R. A., & Opfer, V. D. (2012). Learning 21st-century skills requires 21st-century teaching. *Phi Delta Kappan, 94*(2), 8–13.

Sanders, M. (2009). Integrative STEM education: Primer. *The Technology Teacher*, *68*(4), 20–26.

Schroeder, C., Scott, T., Tolson, H., Huang, T-Y, & Lee, Y-H. (2007). A meta-analysis of national research: Effects of teaching strategies on student achievement in science in the United States. *Journal of Research and Science Teaching*, *44*(10), 1436–1460.

Scott, C. (2012). An investigation of science, technology, engineering and mathematics (STEM) focused high schools in the US. *Journal of STEM Education: Innovations & Research*, *13*(5).

Shaughnessy, J. M. (2013). By way of introduction: Mathematics in a STEM context. *Mathematics Teaching in the Middle School*, *18*(6), 324.

Stinson, K., Harkness, S. S., Meyer, H., & Stallworth, J. (2009). Mathematics and science integration: Models and characterizations. *School Science and Mathematics*, *109*(3), 153–161.

Stohlmann, M., Moore, T. J., McClelland, J., & Roehrig, G. H. (2011). Impressions of a middle grades STEM integration program: Educators share lessons learned from the implementation of a middle grades STEM curriculum model. *Middle School Journal*, *43*(1), 32–40.

Subotnik, R. F., Tai, R. H., Rickoff, R., & Almarode, J. (2009). Specialized public high schools of science, mathematics, and technology and the STEM pipeline: What do we know now and what will we know in 5 years? *Roeper Review*, *32*(1), 7–16.

Tai, R. H. (2012). *An examination of the research literature on Project Lead the Way*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.361.548&rep=rep1&type=pdf

Timms, M., Moyle, K., Weldon, P., & Mitchell, P. (2018). *Challenges in STEM; earning in Australian schools: Literature and policy review*. Australian Council For Educational Research.

Tran, N. A., & Nathan, M. J. (2010). Pre-college engineering studies: An investigation of the relationship between pre-college engineering studies and student achievement in science and mathematics. *Journal of Engineering Education*, *99*(2), 143–157.

Treacy, P., & O'Donoghue, J. (2014). Authentic Integration: A model for integrating mathematics and science in the classroom. *International Journal of Mathematical Education in Science and Technology, 45*(5), 703–718.

Valkanova, Y., & Watts, M. 2007. Digital story telling in a science classroom: Reflective self-learning (RSL) in action. *Early Child Development and Care*, *177,* 793–807.

Van Overschelde, J. P. (2013). Project Lead the Way students more prepared for higher education. *American Journal of Engineering Education*, *4*(1), 1–12.

Weinberg, A. E., & Sample McMeeking, L. B. (2017). Toward meaningful interdisciplinary education: High school teachers' views of mathematics and science integration. *School Science and Mathematics*, *117*(5), 204–213.
Wiswall, M., Stiefel, L., Schwartz, A. E., & Boccardo, J. (2014). Does attending a STEM high school improve student performance? Evidence from New York City. *Economics of Education Review*, *40*, 93–105.
Yasin, R., Amin, L., & Hin, K. (2018). Teaching & learning of 21st century biotechnology in secondary school additional science. *Teaching Science*, *64*(3), 27–36.