Queensland University of Technology
Brisbane Australia

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Advancing Elementary and Middle School STEM Education

Lyn D. English

Abstract

Navigating the current STEM agendas and debates is complex and challenging. Perspectives on the nature of STEM education and how it should be implemented without losing discipline integrity, approaches to incorporating the arts (STEAM), and how equity in access to STEM education can be increased are just a few of the many issues faced by researchers and educators. There are no straightforward answers. Opinions on how STEM education should be advanced vary across school contexts, curricula, and political arenas. This position paper addresses five core issues: (a) perspectives on STEM education; (b) approaches to STEM integration; (c) STEM discipline representation, (d) equity in access to STEM education, and (e) extending STEM to STEAM. A number of pedagogical affordances inherent in integrated STEM activities are examined, with the integration of modeling and engineering design presented as an example of how such learning affordances can be capitalized on.

Key Words: STEM education, STEM integration, STEM access, STEAM education, pedagogical affordances, modeling, engineering design, programming and computational thinking

Introduction

STEM competencies (science, technology, engineering, and mathematics) are receiving escalating global attention, with these skills increasingly in demand not only within, but also beyond, specific STEM occupations (e.g., Commonwealth of Australia, 2015; Education Council, 2015; European Parliament, 2015; Marginson, Tytler, Freeman, & Roberts, 2013; National Science and Technology Council, 2013). Considered essential to promoting innovation, productivity, and overall economic growth, STEM education is seen as critical across many nations, fuelled in part by perceived or actual shortages in the current and future STEM workforce (e.g., Caprile, Palmen, Sanz, & Dente, 2015; Charette, 2013; Hopkins, Forgasz, Corrigan, & Panizzon, 2014; The Royal Society Science Policy Centre, 2014). Analyses of results from international comparative assessments (e.g., OECD, 2016) have further sparked this STEM activity.

Navigating the current STEM agendas is complex and challenging. Suggesting approaches to advancing STEM education is even more difficult. It is not possible to do justice to the many issues raised in the literature nor to address the range of possible future directions for STEM education in schools. Five issues, however, appear prominent in both the academic literature and in the media, and form the focus of this position paper. These have been singled out because they impact directly on policy and curriculum decisions, and thus warrant attention in efforts to improve STEM education in the classroom. These issues include: (a) perspectives on STEM education; (b) approaches to STEM integration; (c) STEM discipline representation, (d) equity in access to STEM education, and (e) extending STEM to STEAM (incorporating the arts). A number of pedagogical affordances inherent in integrated STEM activities are examined, with the integration of modeling and engineering design presented as an example of how such affordances can be capitalized on.

Perspectives on STEM Education

Foundational to discussions on how STEM education might be enhanced are the various perspectives on what STEM entails. It is beyond the scope of this article to address the myriad viewpoints, which vary in scope and specificity (e.g., Bryan et al., 2016; Bybee, 2013; Charette, 2014/2015; Sanders, 2009; Stohlman, Moore, & Roehrig, 2012; Vasquez, Schneider, & Comer, 2013). As Bybee (2013) noted, defining educational terms is invariably contentious:

> There is an interesting paradox I have observed concerning definitions in education: Many request a definition, and few agree with one when it is presented. So it is with STEM education. The meaning or significance of STEM is not clear and distinct. There is reference to four disciplines, but sometimes the meaning and emphasis only include one discipline. In some cases, the four disciplines are presumed to be separate but equal. Other definitions identify STEM education as an integration of the four disciplines. (p. x).

One definition of STEM education that appears especially apt in highlighting the mathematics and science disciplines within the STEM space is that offered by Shaughnessy (2013): “STEM education refers to solving problems that draw on concepts and procedures from mathematics and science while incorporating the team work and design methodology of engineering and using appropriate technology” (p. 324). Nevertheless, as Bybee (2013) indicated, there remains considerable debate and confusion on what STEM education involves, on whether the disciplines should be integrated and to what extent, and even on whether the acronym itself should continue to be used (e.g., Williams, 2011).

Within these debates, STEM integration appears to be increasingly emphasized, reflecting the interdisciplinary solutions required in tackling today’s complex economic, social, and environmental problems (e.g., Bryan et al., 2016; English, 2016; Honey, Pearson, & Schweingruber, 2014; Sanders, 2009). Irrespective of what definition is adopted, whether within a state, a nation, or globally, it needs to be consistent in achieving the desired educational aims, workable and accessible by all, and address the core content and processes of the respective disciplines. This caveat is especially germane when STEM integration is advocated.

Approaches to STEM Integration

> School subjects tend to be taught in isolation from each other, at a time when solutions to societal challenges and the nature of work are becoming increasingly cross-disciplinary (Masters, 2016, p. 6).

Viewpoints on STEM integration vary, with Honey et al. (2014) defining it simply as “Working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines” (p. 52). Even the use of the term, *integration* has been questioned. Sanders (2012) and Wells (2013), for example, argued that “integrative STEM” and “STEM integration” are quite distinct, with *integrative* indicating an “ongoing, dynamic, learner-centered process of teaching and learning”, as distinct from *integrated*, which suggests a more static, teacher-directed process (p. 29).

Several arguments are offered for the advantages of STEM integration including as a means for adding meaning to and linking students’ learning across the STEM disciplines, its relevance to tackling real-world problems, and the increasing use of multidisciplinary teams across many professions. It is frequently contended that many of the prevalent approaches to STEM education in schools do not reflect the natural way in which the disciplines are connected in the real world (Moore, Glancy, Tank, Kersten, Smith, Karl, & Stohlmann, 2014; National Research Council, 2009; STEM Taskforce Report, 2014). The STEM Task Force Report (2014) expressed the succinct argument that STEM education is far more than a “convenient integration” of its four disciplines, which "cannot and should not be taught in isolation, just as they do not exist in isolation in the real world or the workforce” (p.9).

The challenge for STEM educators lies in how the disciplines can be effectively integrated while at the same time ensuring the integrity of each. This challenge cannot be ignored, given the number of curriculum documents advocating some form of integration. The US *Common Core State Standards for Mathematics* (http://www.corestandards.org/Math/), the *Next Generation Science Standards* (http://www.nextgenscience.org/), the Australian *Design and*

Technologies Curriculum (ACARA, 2015), and the British Council Thailand's STEM education programme (2016; https://www.britishcouncil.or.th/en/programmes/education/our-work-support-higher-education-and-research-sector/NewtonFund/stem-education) all incorporate approaches to integrating the disciplines. Extending STEM to STEAM is increasingly in popularity, having been mandated by the Korean government where the arts are incorporated to lift students' interest in and understanding of science (Jho, Hong, & Song, 2016).

Numerous frameworks for implementing STEM integration have been proposed including those of Vasquez et al. (2013), where different forms of boundary crossing are displayed along a continuum of increasing levels of interconnection and interdependence among the disciplines. Beginning with simple disciplinary approaches, where concepts and skills are learned separately in each discipline, the continuum progresses to multidisciplinary forms involving concepts and skills in each discipline being learned separately but within a common theme. Finally, transdisciplinary approaches encompass knowledge and skills learned from two or more disciplines applied to real-world problems and projects, thus shaping the total learning experience.

Offering a more detailed approach to STEM integration, Bryan, Moore, Johnson, and Roehrig (2015) proposed a "STEM Roadmap" where they warned that STEM integration is not simply teaching two disciplines together or using one as a tool for teaching another; many educators are already doing this. Rather, STEM integration needs to be "intentional" and "specific" with consideration given to both content and context. They identify three forms of STEM integration: (a) content integration where learning experiences have multiple STEM learning objectives; (b) integration of supporting content where one area is addressed (e.g., mathematics) in support of the learning objectives of the main content (e.g., science), and (c) context integration where the context from one discipline is used for the learning objectives from another. While the integration of supporting content is frequent, it appears not to be applied in a way that effectively extends this content (Bryan et al., 2015).

Table 1 presents a simple STEM integration matrix, which I offer as just one tool for analysing and categorizing the content and context of integrated activities that might be incorporated within a school curriculum. Features inherent in the matrix include the nature and extent of disciplinary content (and processes) integration (primary, supporting, or absent), and the nature and extent of context integration (one or more disciplinary contexts and/or background contexts, examples of which are listed). A possible problem structure is displayed where mathematics and engineering form the primary content areas, with science as the supporting content. Engineering, along with technology, provides the disciplinary context, while societal and historical issues form the background context. The matrix could serve to identify broadly the balance of disciplinary content coverage and the range of problem contexts employed across a suite of STEM problems. The matrix could be further refined to encompass topics within each discipline. The importance of both content and context is evident in the 2015 PISA mathematics framework (OECD, 2015), with four categories of each providing the basis for the PISA test items, namely: “Quantity; Uncertainty and data; Change and relationships; and Space and shape” (content), and personal, societal, occupational, and scientific (context) (p. 6).

Given the foregoing arguments for, and approaches to STEM integration, there remains a core issue open to debate, namely, to what extent should students’ learning of the STEM disciplines be governed by integrated activities? Although I consider appropriately developed integrated STEM activities and their timely introduction as paramount to advancing the field, I do not advocate total integration. It is questionable whether such an approach would do justice to students’ learning of core disciplinary content and processes. Rather, an integrated STEM activity is ideal for consolidating and extending units of disciplinary study, such as concepts of light in science and measurement processes in mathematics forming the basis for applying STEM ideas in building an optical instrument (King & English, 2016).

Table 1
Sample STEM Integration Matrix

Content	**Science**	**Technology**	**Engineering**	**Mathematics**	**(Arts)**
Primary			√	√	
Supporting	√				
Context	**Science**	**Technology**	**Engineering**	**Mathematics**	**(Arts)**
Disciplinary		√	√		
Background	**Personal**	**Societal**	**Occupational**	**Historical**	**Other**
		√		√	

Promoting Equitable Discipline Representation

With the rapid rise of STEM education as an interdisciplinary construct, many researchers have expressed concerns over emerging inequitable discipline attention (e.g., English, 2015; English & King, 2016; DiFrancesca, Lee, & McIntyre, 2014; Honey et al., 2014; Moore et al., 2014). The STEM acronym is frequently used in reference to science (Bybee, 2013; Office of the Chief Scientist, 2014), with many nations referring to the role of STEM education as one that fosters “broad-based scientific literacy,” with a key objective being “science for all” in efforts to lift science education in the elementary, middle, and secondary school curricula (Marginson et al., 2013, p. 70). As Marginson et al. pointed out, STEM discussions rarely adopt the mantra, “mathematics for all,” even though mathematics underpins the other disciplines. They thus argued that “the stage of mathematics for all should be shifted further up the educational scale” (p.70). In a similar vein, Shaughnessy (2013) warned of programs that are merely a STEM veneer, that is, where approaches do not genuinely integrate the disciplines and hence may be devoid of important learning especially in mathematics. Interestingly, mathematics as a core discipline was not featured in the prominent *Discipline-based Education Research Report* (Singer, Nielsen, & Schweingruber, 2012), where the focus was on science (e.g., geoscience, physics, chemistry, biology) and engineering.

Engineering education, particularly in the elementary and middle school, is severely neglected and tends to remain the silent member of the STEM acronym. The contributions of engineering education, in particular, engineering design processes, to younger students' learning are not being adequately recognized in many nations. Yet as Katehi, Pearson, and Feder (2009) emphasized, "In the real world, engineering is not performed in isolation – it inevitably involves science, technology, and mathematics. The question is why these subjects should be isolated in schools" (pp. 164–165).

In recent years, researchers and curriculum developers have lauded the contributions of engineering education to the advancement of STEM learning. For example, engineering provides a real-world context for linking students' learning of science, mathematics, and technology, as well as for developing their problem-solving, communication, and teamwork skills (English & King, 2017). As indicated later, engineering design processes provide important foundational links across the STEM disciplines and enable students to appreciate how multiple ideas, approaches, and tools can be applied to complex problems involving more than one solution (Purzer, Hathaway Goldstein, Adams, Xie, & Nourian, 2015).

Engineering is frequently overshadowed by technology and at times, science. Technology educators, for example, have warned against their discipline being linked with engineering. Williams (2011) even argued that "STM would be more appropriate [acronym] because engineering is actually a sub-set of the broad area of technology" (p. 30). Sanders (2009, 2012), on the other hand, embraced the inclusion of engineering and technology in enhancing the teaching and learning of mathematics and science:

> Integrative STEM education refers to technological/engineering design-based learning approaches that intentionally integrate content and process of science and/or mathematics education with content and process of technology and/or engineering education (Sanders, 2012, p.2).

As featured in the matrix (Table 1), engineering is not only a discipline in its own right but also can provide a rich source of supporting content and engaging problem contexts.

Engineering education needs greater recognition and elevation in STEM programs especially in elementary and middle school education (e.g., DiFrancesca, Lee, & McIntyre, 2014; English & King, 2016; Hoachlander, 2014/2015; Moore et al., 2014). The omission of the discipline is a major impediment to advancing all of STEM education. The inclusion of engineering within the US *NGSS* is a positive step, but acceptance of the discipline within schools has a considerable distance to go, as Hoachlander (2014/2015) lamented:

> Despite more than a decade of strong advocacy by practitioners, employers, and policymakers, STEM education in U.S. schools leaves a great deal to be desired. In too many schools, science and math are still taught mostly in isolation from each other, and engineering is absent (p. 74).

Although raising the presence of engineering in the elementary and middle grades is advocated here, assigning equal curriculum time to the discipline would not seem feasible in many already crowded curricula. However, given the significant contributions of engineering and engineering design processes to STEM education, the discipline clearly warrants increased prominence within the curriculum; its potential for enriching the other disciplines and for fostering an early interest in STEM learning cannot be overlooked.

In contrast to engineering as the underrepresented member of STEM education, technology is enjoying an upsurge. With the rapidly increasing popularity of computer programming (coding) in schools and the broadening of the associated computational thinking skills, the STEM education landscape is rapidly changing (e.g., Gadanidis, Hughes, Minniti, & White, 2016; Schneider, Stephenson, Schafer, & Flick, 2014; Weintrop, Beheshti, Horn, Orton, Jona, Trouille, & Wilensky, 2016; Wing, 2006). Computational thinking in particular, is undergoing substantial change and remains an area in need of further research.

Traditionally, computational thinking has tended to have a narrow focus, being viewed as an isolated technology curriculum component rather than possessing rich potential for inclusion in integrated STEM programs (Gagdanidis et al., 2016; Weintrop et al., 2016). Following Wing's (2006) seminal article, however, on the omnipresent nature of computational thinking in our lives, STEM educators have begun to apply features of this thinking to their research and teaching. For example, Weintrop et al. (2016) commented that "Science and mathematics are becoming computational endeavors" (p. 127), with a reciprocal relationship existing between the domains. That is, computational thinking can enhance mathematics and science learning, and mathematics and science contexts can enrich computational thinking. To this end, Weintrop et al. (2016) proposed an interrelated taxonomy of computational thinking in mathematics and science comprising practices in data, modeling and simulation, problem solving involving computational thinking, and systems thinking.

The heightened interest in computer programming and computational thinking gives rise to opportunities for mathematics education to increase its presence on the STEM landscape, as evident in Schneider et al.'s (2014) framework. Specifically, Schneider et al. emphasise the relationship between mathematical and computational thinking where problem solving, modeling, analysing and interpreting data, and statistics and probability are identified as shared features. With computer programing and the associated computational thinking skills being treated in isolation rather than being integrated within the curriculum, we know comparatively little about how these programming skills can enhance the learning of the other disciplines such as mathematics. This situation is cause for concern, given the upsurge in computer programs designed for younger learners such as *Scratch Jr,* an introductory programming language that enables five- to seven-year-olds to develop their own interactive games and stories (Strawhacker & Bers, (2015). A number of issues thus appear in need of attention, including, but certainly not limited to the following:

(a) What is the nature of young children's learning as they engage in popular coding programs?

(b) How does this learning support the other STEM disciplines in particular mathematics and science?

(c) To what extent is there a reciprocal relationship between computational thinking and mathematical learning and problem solving? and

(d) How can computational thinking be integrated within STEM programs to facilitate the early development of a broader range of topics (e.g., geometry and probability in mathematics, as featured in Gadanidis et al.'s, 20216, research)?

The sentiments of Gadanidis et al. are especially apt in considerations of advancing STEM education commencing with the youngest learners. In introducing mathematics ideas from the upper secondary school curriculum into the early grades, these researchers were interested in:

> investigating, depicting and learning from cases of "what might be" (or "what ought to be"), to disrupt common conceptions of what CT and mathematics are accessible to young children, how they might engage with it, and how CT affordances may affect mathematics teaching and learning.

These sentiments are applicable right across the STEM disciplines. In arguing for a more equitable focus on the disciplines, this section has suggested ways in which we might avoid the STEM acronym being referred to as simply "science". Although science and mathematics have traditionally been core discipline areas and rightly so, if society and educators are to continue to advocate for improved learning in *STEM*, then each discipline needs to be acknowledged and promoted. Depriving students of valuable learning across all of STEM is an injustice, especially given young students' potential and enthusiasm for learning in these areas (Early Childhood STEM Working Group, 2017). Increasing learner access to quality STEM education ("what ought to be") remains a key issue for future research, not only with respect to socio-economic, gender, and ethnicity factors, but also in terms of capitalizing on and extending the capabilities of all learners.

Increasing Access to STEM Education

Issues pertaining to learner equity in access to and success in the STEM fields are manifold; possible directions for addressing these cannot be covered adequately in a brief section of one article. Concerns regarding disparity between the STEM achievements of students across schools, socioeconomic domains, and ethnic and gender backgrounds remain in the spotlight. For example, in the launch of the PISA 2015 results (6 December, 2016; http://www.oecd.org/pisa/launch-of-pisa-2015-results.htm), alarms were raised that, in the period from 2006 to 2015, no nation or economy improved its performance in science and equity simultaneously. Strategies for arresting disparities in STEM achievement are inviably complex involving multiple interacting factors (e.g., Masters, 2016; Vale, Atweh, Averill, & Skourdoumbis, 2016).

Masters (2016) highlighted the trend in several nations to implement policies to reduce between-school differences, thus making student outcomes less dependent on the school they attend or the socioeconomic area in which they reside. This approach invariably requires substantial policy shifts, which can be open to challenges from many quarters. Nevertheless, some nations (e.g., Finland) have demonstrated how government policies designed to minimize the impact of between-school differences can succeed in improving STEM learning for more students.

The recommendations of Masters (2016) offer some ways forward in advancing STEM education although not all are likely to be achievable in the short term. Promoting effective school improvement and curriculum practices, and maximising access to quality teachers and school leaders are advocated. Changes to curricula, school practices, and teacher education, however, are often subjected to forces stemming from political, industrial, and social cycles where recommended changes might not necessarily align with what educators deem important in promoting STEM education. Masters' (2016) other recommendations, which appear more achievable within a given classroom or school, include meeting "all students at their points of need with learning opportunities that stretch and extend them" (p. 16), and customising teaching and learning to ensure students' current readiness and achievement levels are identified and built upon. Integrated STEM-based activities lend themselves effectively to providing learning opportunities that not only meet students' current levels but also extend them. These points are revisited in the final section of this article.

STEAM Education

As noted previously, STEAM education is gaining traction in some nations and could be seen as another approach to increasing learner access to STEM through targeting students' interest in the arts. Returning to the STEM integration matrix, the addition of the arts could provide not only new disciplinary learning content but also real-world contexts that cater for more diverse student interests. Engineering for instance, as one of the key disciplines shaping our environments, draws on both content and contexts from the arts. Bridge design and construction, as just one example, involves substantial consideration of aesthetics as can be seen in the world's many famous bridges. Successful bridge designers must consider both the abstract structural form and how the bridge resides within its surroundings: "A bridge designed without consideration of aesthetics can serve its function, but can be an unattractive and visual barrier" (Evamy, 2005, p.iii).

Marrying art with science and technology can also be seen in numerous real-world cases. In quoting the “top ten lessons Steve Jobs taught us”, Jackson (2011) cited the first as “The most enduring innovations marry art and science” (http://www.forbes.com/sites/ericjackson/2011/10/05/the-top-ten-lessons-steve-jobs-taught-us/#61b8cad462f6). The original team developing the Mac comprised personnel from multiple disciplinary backgrounds including art, anthropology, history, and poetry. To illustrate this point, Jackson (2011) referred to the difference between the iPad and other tablet computers as “the look and feel of a product. It is the soul.” The importance of the arts to technology and engineering cannot be underestimated, with its potential contributions requiring substantially more attention.

The STEAM curriculum in Korea provides one example of a nation that has implemented such a program as a major educational policy. In doing so, Korea aims to nurture the “creative and all-round talents” of all its students especially in science and technology, and to increase the nation’s competitiveness (Jho et al., 2016; Kim & Bolger, 2016). Although STEAM education appears potentially rich in fostering the engagement and learning of more students, it presents numerous challenges including the preparedness, willingness, and confidence of teachers to embrace such a curriculum, as Kim and Bolger (2016) emphasize.

In implementing any STEAM program, ensuring each of the disciplines is being adequately developed is critical. The addition of a fifth discipline generates extra issues in designing and actually implementing lessons that meet the objectives of the respective learning areas. Furthermore, as Kim and Bolger (2016) pointed out, aligning broad curricula goals and the details of specific lesson plans (i.e., do the various learning aspects “work well together?”) needs more careful consideration. There is the danger of misalignment when different groups of educators are assigned to the creation of standards and policy documents, and to the writing of lesson plans and textbooks. Establishing productive communities comprising teachers and leaders from the respective STEAM disciplines is one approach to addressing this concern, as evident in Jho et al.'s (2016) findings.

STEAM education appears to remain under researched compared to STEM education. Of the many questions requiring attention, the issue of developing curricula that teachers feel comfortable with and confident in implementing while at the same time covering the required content and processes would appear foremost. Although the contributions of the arts to the other disciplines cannot be underestimated, the practical issues pertaining to teacher preparedness and appropriate curriculum resources remain uppermost. The challenges facing integrated STEM education are numerous; adding a fifth dimension increases the complexities educators face. Nevertheless, countries that have adopted STEAM education can provide valuable insights for those wishing to follow this path. Again, whether such an integrated curriculum can be implemented successfully as a complete program of study is debatable.

DESIGNING INTEGRATED STEM-BASED EXPERIENCES

Returning to Masters' (2016) recommendations for fostering students' learning in the 21st century, meeting students' readiness levels and extending their capabilities can be especially facilitated when well-designed, integrated STEM experiences are implemented. The learning affordances provided by linking STEM content and utilising their real-world contexts are numerous. In this final section, I offer a number of recommendations for designing STEM-based learning experiences, drawing in part on the *pedagogical affordances* associated with the earlier programming environments (Grover & Pea, 2013) and applied more recently by Gadanidis and his colleagues (Gadanidis et al., 2016; Gadanidis & Hughes, 2011).

Learning Affordances within Integrated STEM Activities

Studies conducted by Gadanidis and his colleagues have revealed how young students' mathematical learning can be enriched and extended through designing activities that have *low floors, high ceilings,* and *wide walls*, and generate *conceptual surprises* for both the students and the teachers. These pedagogical affordances apply equally to integrated STEM activities. A low floor design enables engagement with minimal disciplinary content knowledge, where students can tackle the activity at their entry or readiness level. The high ceilings afford students opportunities to extend their thinking and learning, often to entertain ideas that are beyond their grade level. The focus of the activity then becomes one of learning or idea generation, rather than just the application of routine procedures or problem-solving strategies. As is well documented, situating students at the centre of their learning where they are encouraged to engage with meaningful yet challenging problematic situations can lead to the application of higher levels of cognitive reasoning (Hunter, Hunter, Jorgensen, & Choy, 2016; Silver, Mesa, Morris, Star, and Benken, 2009). Young learners are readily capable of such extended, high-ceiling learning as I have indicated in numerous studies (e.g., English, 2013). Furthermore, it is not just the usually "higher-achieving" students who excel here; rather, those who are relegated to a "low-achieving" status as measured by their performance on national and international tests frequently display surprising gains in their learning.

Students' conceptual surprises as they uncover new ideas are evident in many integrated STEM-based problems. For example, in designing and constructing an earthquake-proof building, 6th-grade students displayed conceptual surprise as they discovered how construction materials, their measurements and costs, as well as the structural shapes chosen and the engineering techniques used, all contributed to strengthening and stabilizing their building (English, King, & Smeed, 2016). Students' experimentation with engineering design and principles facilitated their appreciation and understanding of how engineering plays a major role in improving and protecting infrastructure and the surrounding environment. Creating STEM-based experiences that feature wide walls encourages students to share and communicate their learning not only within the classroom but beyond, as students convey to others the conceptual surprises they have experienced.

STEM-based activities that feature the foregoing pedagogical affordances should also take into account important social justice issues. In a study by Atweh and Ala'i (2012) efforts to implement "Socially Response-able Mathematics" activities were hampered by teachers' reluctance to use “open ended pedagogies” (p. 103). Their study revealed that when teachers use such approaches, in contrast to direct teaching, students invariably demonstrate a “deeper understanding and engagement in the class” (p. 103). Alleviating possible reticence to implementing more cognitively demanding, low floor, high-ceiling activities that generate conceptual surprises would seem a core plank in our efforts to promote all students' learning across the STEM disciplines.

Learning Affordances in Integrating Modeling and Engineering Design

As one example of how the foregoing pedagogical affordances could be enacted within STEM-based activities, consideration is given to the links between modeling and engineering design processes. The terms, *models* and *modeling*, have been applied variously in the literature including conducting mathematical simulations, generating representations of real-world problem situations, and engaging in a bidirectional process of translating between a real-world situation and mathematics (e.g., Blum & Borromeo Ferri, 2009; English, Arleback, & Mousoulides, 2016; Gravemeijer, 1999; Greer, 1997; Lesh & Doerr, 2003; Romberg, Carpenter, & Dremock, 2005). It is beyond the scope of this article to address these various notions, which have received substantial coverage in the literature. Rather, for this article, I propose STEM-based modeling as a cyclic, generative learning activity where the processes of modeling and engineering share common features and facilitate the solving of authentic problems involving STEM content, processes, and contexts. As used here, "generative" refers to a problem feature where learning of content and/or processes is elicited by the student, rather than provided. Because STEM-based modeling activities provide multiple entry and exit points, and encourage generative learning, they display the desired *low floor* and *high ceiling* features. These activities also exhibit *wide walls* when students are encouraged to document and prepare reports for communicating their findings to others. Obtaining constructive peer and other feedback facilitates further learning including identifying related situations where the models and modeling processes could be applied with or without adaptation.

Engineering design processes align with the cyclic processes of modelling, yet this important link remains underutilized in creating STEM-based experiences. Numerous articles have highlighted the foundational links provided by engineering design processes (e.g., Carberry & McKenna, 2014; Moore, Miller, Lesh, Stohlmann, & Kim, 2013). As previously noted, engineering design processes provide an ideal vehicle for connecting the STEM disciplines and are not just confined to engineering. Numerous descriptions of engineering design have appeared in the literature, but in general, design processes are considered to be iterative in nature involving: (a) defining problems by identifying criteria and constraints for acceptable solutions, (b) generating a number of possible solutions and assessing these to determine which best meet the problem requirements, and (c) optimizing the solution by systematically testing and refining, including overriding less significant features for the more important (English & King, 2015; Lucas, Claxton, & Hanson, 2014; *Next Generation Science Standards* [NGSS], 2014; National Research Council, 2012).

Zawojewski, Hjalmarson, Bowman, and Lesh (2008) summarized succinctly the links between engineering design processes and the cyclic processes of modeling:

> A problem situation is interpreted, initial ideas (initial models, initial designs) for solving the problem are brought to bear; a promising idea is selected and expressed in a testable form; the idea is tested and information from the test is analysed and used to revise (or reject) the idea; the revised (or a new) idea is selected and expressed in a testable form; etc. (p.6).

The iterative nature of both engineering design and modeling can be particularly powerful for school students as it prompts them to test and revise a possible solution to create the best possible outcome, thus potentially encouraging “learning while designing" or generative learning as previously mentioned. (Crismond & Adams, 2012, p. 744; Hamilton, Lesh, Lester, & Brilleslyper, 2008). Young students’ propensity for applying multiple ideas and approaches to innovative and creative problem solving is regarded as providing a rich basis for fostering early design-based problem solving and thus integrating the STEM disciplines. Yet, establishing these important design and modeling processes are not being capitalized on fully in the elementary and middle schools despite the increased recognition that younger learners can engage effectively in these processes (Dorie, Cardella, & Svarowsky, 2014; English & King, 2015; Portsmore, Watkins, & McCormick, 2012). In the next section, one example of a STEM-based modeling activity drawing on engineering, mathematics, and science, as well as the arts, is presented.

STEM-based Modeling: Bridge Design and Construction

English and Mousoulides (2015) reported on a STEM-based modeling activity implemented in the 6th-grade involving the 2007 structural failure of the 35W Minneapolis Bridge in Minnesota (adapted from Guzey, Moore, & Roehrig, 2010). Students are presented with two tables of data (Tables 2 and 3), together with the problem description. The first set of data comprises key characteristics of four main bridge types, while the second table contains two samples of each of the major bridge types with some of their key features.

The problem statement explains that the Minnesota Public Works Department urgently needs to construct a new bridge in the same location as the collapsed one. Specific parameters to be addressed include a highway length of approximately 1000 feet and a deck of four lanes with additional side lanes. Students are to assist the Department by creating a way (model) for comparing the different bridge types so as to choose the appropriate one to build across each span. Working in small groups, students use the given data to generate, refine, and document their models. All possible factors related to bridge type, materials used, bridge design, safety, and cost are to be considered. On completion, students share with their peers the models they have generated and explain their key findings.

Table 2

Characteristics of the Four Major Bridge Types

Bridge Type	Advantages	Disadvantages	Span range	Material	Design effort
Truss bridge	Strong and rigid framework Work well with most applications	Cannot be used in curves Expensive materials	Short to medium	Iron, steel, concrete	Low
Arch bridge	Aesthetic Used for longer bridges with curves Long life time	Abutments are under compression Long span arches are most difficult to construct	Short to long	Stone, cast iron, timber, steel	Low
Suspension bridge	Aesthetic Light and flexible	Wind is always a concern Expensive to build	Long	Steel rope and concrete	Medium
Cable-stayed bridge	Cables are economical Fast to build, Aesthetic	Stability of cables need to be considered for long span bridges	Medium	Steel rope and concrete	High

Table 3

Examples of Four Major Bridge Types

Name	Type	Total length (feet)	Car Lanes	Constructability	Cost (Present value)

Hennepin Ave	Suspension	1037	6	Easy	$100 million
Golden Gate	Suspension	8981	6	Difficult	$212 million
10th Ave	Arch	2175	4	Difficult	$9 million
Stone Arch	Arch	2100	Bike/ Pedestrian	Difficult	$15 million
Greenway	Cable-stayed	2200	Bike/ Pedestrian	Easy	$5.2 million
Arthur Ravenel Jr.	Cable-stayed	13,200	8	Easy	$62 million
John E. Mathews	Truss	7736	4	Difficult	$65 million
Eagle Point	Truss	2,000	2	Difficult	$2.5 million

The problem statement explains that the Minnesota Public Works Department urgently needs to construct a new bridge in the same location as the collapsed one. Specific parameters to be addressed include a highway length of approximately 1000 feet and a deck of four lanes with additional side lanes. Students are to assist the Department by creating a way (model) for comparing the different bridge types so as to choose the appropriate one to build across each span. Working in small groups, students use the given data to generate, refine, and document their models. All possible factors related to bridge type, materials used, bridge design, safety, and cost are to be considered. On completion, students share with their peers the models they have generated and explain their key findings.

The problem activity comprises engineering concepts, principles, and design processes, together with mathematical reasoning and data-based problem solving involving a consideration of multiple factors. Revisiting the matrix, the activity features both mathematics and engineering as primary disciplinary content, science (environmental factors) as the supporting content, and engineering as the disciplinary context. The history of the bridge collapse provides further context for supporting the activity. An important inclusion of the arts is evident as the aesthetics of bridge design are considered.

The activity engages students in multiple modeling cycles as they work towards creating a model that they consider will meet the Department's requirements. The low floor/high ceiling features of the activity enable the creation of a number of models of varying sophistication with respect to the factors considered and how these are operated on. Factors include bridge dimensions, the numbers and types of lanes, the cost per surface unit of a bridge deck, the difficulty level of bridge design and construction, and the aesthetics of the bridges. Students might choose to ignore some factors in model generation (e.g., variation in bridge lengths and number of lanes) or incorporate other factors such as relative times for bridge construction, the stability of the bridge types, whether one bridge type is more aesthetically pleasing than another, and emotional issues associated with the type of collapsed bridge. A consideration of trade-offs might also take place, such as choosing a more expensive bridge type because of a concern regarding the stability of a less expensive type.

The foregoing example is one of many that can be developed to capitalize on, and extend, students' learning in the respective STEM disciplines. Activities of this nature can be further enhanced through the inclusion of apps enabling, for example, a wider range of bridge types, construction materials, and associated costs to be considered. The example also provides a template that could be used to create problems involving other real-world STEM examples, such as determining suitable countries from which to import particular products taking into consideration commodity prices, product manufacturing quality, mode of transport and freight costs, environmental and safety issues, and so on.

Concluding Points

This article has reviewed some of the issues and challenges facing STEM education today. Internationally, this domain continues to be a topic of much debate as nations attempt to develop more STEM-literate communities (e.g., Goldman & Zielezinski, 2016). Although we can anticipate that STEM competencies will be increasingly needed in our ever-changing world, it is difficult to predict which of the many approaches to advancing STEM education will be most effective.

There appear several dilemmas facing educators in trying to promote STEM competencies. Among the many, it seems that discipline integrity and equitable discipline attention in STEM agendas and programs are paramount, especially when various forms of integration are advocated. In particular, the “E” in STEM often appears ignored or given a much lower status in reports on promoting STEM skills. We might thus ask if some educators are “protecting” their respective disciplines. For example, is engineering and its design processes considered unnecessary given their inclusion within existing science and technology curricula? The incorporation of engineering practices alongside those of science in the *NGSS* is a positive and welcomed advancement, as is the inclusion of engineering principles and design within the *Australian Curriculum: Design and Technologies* (ACARA, 2915).

Likewise, we could question whether mathematics is being accorded its rightful place in STEM agendas. That is, is the reciprocal relationship between mathematics and the other STEM domains being fully recognized? As Fitzallen (2015) argued, many reports claim that STEM provides contexts for fostering mathematical competencies but these reports do not acknowledge this reciprocal relationship. That is, the ways in which “mathematics can influence and contribute to the understanding of the ideas and concepts of other STEM disciplines” (p. 241) appear to be given inadequate attention.

Computer programming and the associated computational thinking are enjoying renewed and broadened interest in recent times, but it is questionable whether their popularity is being adequately matched by research outputs. Although research is being undertaken, mostly with older students (e.g., Swaid, 2015), substantially more is needed especially with respect to the elementary and middle grades. Furthermore, as Grover and Pea (2013) highlighted, without a greater focus on assessment of learning with computational thinking, it is difficult to determine what learning is taking place. I have raised just a few areas that appear in need of attention in computer programming, including the nature of students' learning and how it can be more effectively connected to the other STEM disciplines. Nevertheless, large gaps in the research still exist, calling for more empirical studies including drawing on research of the 1980s where extensive cognitive aspects of young students' computational learning were examined (Grover & pea, 2013). In the words of Grover and Pea, we need a "more lucid theoretical and practical understanding of computational competencies in children" (p. 42).

The extension of STEM education to incorporate the arts (STEAM) can enrich the basic integration matrix proposed earlier and also go some way towards increasing equity in access to STEM education through reaching a broader range of student interests. Although STEAM education holds considerable promise, it presents additional challenges for teachers and curriculum designers in ensuring the respective disciplines are given adequate coverage and are linked meaningfully and effectively. Teacher confidence and willingness to implement a STEM or STEAM program in which two or more of the disciplines are integrated are essential, as are curriculum resources to facilitate such implementation.

Research has indicated the difficulties teachers face in making appropriate links across the STEM domains, frequently resulting in students becoming disinterested in science and mathematics when they are taught in isolation devoid of connections to cross-cutting ideas and real-world applications (Kelley & Knowles, 2016). Future directions need to include teacher professional development where implementable frameworks for integrated STEM education and associated curriculum resources are available (Moore, Stohlmann, Wang, Tank, Glancy, & Roehrig, G., 2014; Nedelson, Seifert, Moll, & Coats, 2012).

If these challenges are met, well designed STEM and STEAM experiences can provide learning affordances that enable the engagement of a more diverse range of students. With varying entry and exit points, combined with opportunities to entertain new and more advanced concepts, such experiences have the potential to increase students' achievement and motivation levels. Connecting modeling and engineering design has been offered as one example of how learning affordances of integrated STEM programs can be capitalized on. As long as the integrity of the respective disciplines is maintained and teachers are equipped with the necessary knowledge, commitment, and resources, curricula that incorporate one or more forms of integrated STEM/STEAM activities would seem a positive step for advancement. In today's world where multidisciplinary approaches and skills are required for solving increasingly complex problems, further research on how integrated STEM experiences can be more effectively designed and implemented to support and enhance the existing curriculum would appear one of our priorities.

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