STEM Education: What Does Mathematics Have To Offer?

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The emphasis on science, technology, engineering, and mathematics (STEM) education in recent times could be perceived as business as usual or as an opportunity for innovation and change in mathematics classrooms. Either option presents challenges for mathematics educators who are expected to contribute to the foundations of a STEM literate community. A greater understanding of the implications of a STEM education for mathematics education is needed. This paper seeks to add to conversations about the implications of STEM education for the learning and teaching of mathematics.

Ongoing calls for strengthening the nation's skills in Science, Technology, Engineering, and Mathematics (STEM) (Australian Industry Group, 2013; Marginson, Tytler, Freeman, & Roberts, 2013) are fuelled by the imperative to foster national and global economic growth. For this to occur, it is acknowledged that it is necessary to generate more graduates who have the capacity to pursue science-based careers in the future (Office of the Chief Scientist [OCS], 2013). In Australia, however, it is considered that there is:

> …too little time on average spent teaching science in primary school; declining interest in the study of STEM disciplines in senior secondary school; limited growth, even decline in particular areas of the natural and physical sciences, in branches of engineering and information technology at tertiary level; and STEM skill shortages in the workforce. (Office of the Chief Scientist, 2013, p. 10)

As a result, there have been efforts to promote STEM education and what it has to offer. For example, the publication, *Australia's Future: STEM Launches Stars into Orbit* (OCS, 2014), showcases a diverse range of young, high achieving scientists who have forged careers in STEM fields. The profiles presented give brief descriptions of each individual's motivation, interest, experience at school, and pathway to the chosen career. Common to many of the profiles are participation in extension activities while at school, such as the Science, Mathematics, Physics, or Chemistry Olympiads. These are learning opportunities made available to students who are identified as exceptional or talented in those fields of study. This sort of publication serves to highlight the diversity of innovation and career pathways possible in Australia but does little to support teachers to enact a curriculum that will fulfil the expectations of "developing a scientifically literate and numerate society... [and] nurturing student interest in science and influencing their study and career choices" (OCS, 2013, p. 14) in regular mathematics classrooms.

To take advantage of career opportunities in the future, individuals need to develop 21st century skills, which include critical thinking, team work, problem solving, creativity, analytic reasoning, and communication (Bowman, 2010). These are evident when individuals "can manage their own wellbeing, relate well to others, make informed decisions about their lives, become citizens who behave with ethical integrity, relate to and communicate across cultures, work for the common good and act with responsibility at local, regional and global levels" (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2013, p. 3). These learning, literacy, and life skills are epitomised in the General Capabilities detailed in the Australian Curriculum, which are Numeracy, Literacy, Information and Communication Technology (ICT) Capability, Critical and Creative Thinking, Personal and Social Capability, Intercultural Understanding, and

2015. In M. Marshman, V. Geiger, & A. Bennison (Eds.). *Mathematics education in the margins* (Proceedings of the 38th annual conference of the Mathematics Education Research Group of Australasia), pp. 237–244. Sunshine Coast: MERGA.

Ethical Understanding. These capabilities align with the notions of literacy that apply to the STEM disciplines: scientific literacy, technological literacy, and engineering literacy, and mathematical literacy (Sneider & Purzer, 2014). However, schools vary in the extent to which they incorporate the development of those skills. Hence, it is worth exploring ways in which STEM education can be implemented effectively.

What is STEM?

In its simplest form, STEM is an acronym for the four independent disciplines of science, technology, engineering, and mathematics, which often involve traditional disciplinary coursework. This view is reflected in the way in which the Australian Curriculum is structured with separate subject areas for each of the disciplines, with the exception of engineering, which is addressed implicitly in the *Australian Curriculum: Technology* and the *Australian Curriculum: Science* (ACARA, 2015). In the US, engineering is included in the *Next Generation Science Standards* (National Academy of Sciences, 2013). It is acknowledged explicitly along with Life science, Physical science, and Earth and space science.

Implementing the school curriculum in subjects that are discreet areas of study limits students' opportunities to develop the 21st century skills touted as being necessary to take advantage of career opportunities in the future (Rennie, Wallace, & Venville, 2012). Relabelling the subject areas and referring to them collectively through the use of the STEM acronym only maintains the "status quo educational practices that have monopolized the [education] landscape for a century" (p. 21) and does not result in changes to educational practices (Breiner, Johnson, Harkness, & Koehler, 2012; Sanders, 2009). At the other extreme, Moore and Smith (2014) suggest there is the potential for STEM to be a "discipline" in its own right. This view is idealistic and is likely to draw much criticism but raises the question "Should STEM be a discipline in the Australian curriculum?" Sanders (2009) suggests this is not viable. One of the reasons given is because the demand on teachers to have sufficient content knowledge as well as pedagogical content knowledge across all of the four STEM disciplines and their integration is too great. Not achieving these demands may result in inadequate content knowledge in some areas, which has the potential to impact negatively on teachers' ability to implement integrative pedagogical approaches in meaningful ways (Treacy & O'Donoghue, 2014).

Conceptually and by its very nature, STEM is interdisciplinary because it is comprised of other disciplines (Treacy & O'Donoghue, 2014). Smith and Karr-Kidwell (2000) conceptualise the interdisciplinary nature of STEM as "a holistic approach that links the [individual] disciplines so that learning becomes connected, focused, meaningful, and relevant to learners" (p. 24). A complementary but different holistic view is offered by Shaughnessy, who suggests "STEM education refers to solving problems that draw on concepts and procedures from mathematics and science while incorporating the teamwork and design methodology of engineering and using appropriate technology" (2013, p. 324). This view harnesses the characteristics of each of the disciplines in an interrelated manner.

Another interrelated integrative approach, *Authentic Integration*, is suggested by Treacy and O'Donoghue (2014). Their model is underpinned by four main characteristics: knowledge development, synthesis and application; focused inquiry resulting in higher order learning; application to real-world scenarios; and rich tasks (Figure 1). This model is applicable to the individual STEM disciplines as well as the integrative notion of STEM. It focuses on the way in which each of the characteristics supports the other characteristics and does not rely on the inquiry processes and ways of working that apply to particular disciplines.

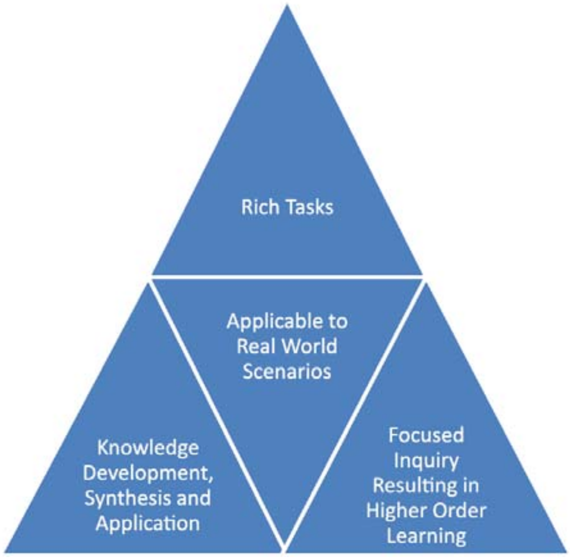

Figure 1. Authentic Integration model (Reproduced from Treacy & O'Donoghue, 2014, p. 710).

Other notions of STEM do not rely on making connections across all four disciplines collectively. They suggest that making connections between/among any two or more STEM disciplines or between/among a STEM discipline and one or more other school subjects is taking an integrative approach (Sanders, 2009). This view gives teachers the freedom to enact STEM through the disciplines with which they are most familiar but does not assure all the disciplines will be addressed sufficiently (Shaughnessy, 2013). Regardless of the extent the disciplines are integrated, the main aim is to support student learning in the traditional content areas (Cardella, Purzer, & Strobel, 2014) and support students to connect content and concepts from the STEM disciplines to create new knowledge (Ostler, 2012).

What Does an Integrative STEM Education Have to Offer?

The integration of STEM subjects is advocated by many as it is seen as a way of engaging students in real-world problems, promoting recall, and enhancing knowledge transfer (e.g., Berry, Chalmers, & Chandra, 2012; Moore & Smith, 2014; Ostler, 2012). It provides ways of placing the learning of mathematics within meaningful contexts and promotes the use of hands-on activities that link to real world problems (Treacy & O'Donoghue, 2014). A potential product of an integrative STEM education is described by Sneider and Purzer (2014) as:

> …a person who has sufficient knowledge and skills in all four fields to participate and thrive in the modern society with confidence and the capacity to use, manage, and evaluate the technologies prevalent to everyday life, as well as the capacity to understand scientific principles and technological processes necessary to solve problems, develop arguments, and make decisions. (p. 9)

It is very desirable for students to develop these capabilities, which are analogous with the expectations of the Australian Curriculum (ACARA, 2015). It is reported that integrative approaches improve students' interest and learning in STEM (e.g., Bottge, Grant, Stephens, & Rueda, 2010; Moore & Smith, 2014; Moore, Stohlmann, Wang, Maruyama Tank, & Roehrig, 2014; Mulligan & English, 2014) yet little evidence is available about the effectiveness of the varying integrative approaches. An exception is a study that reported on a meta-analysis of 98 studies that were identified as investigating the effects of integrative approaches among STEM subjects (Becker & Park, 2014). The meta-analysis included a synthesis of the results reported for seven types of integration: E-M-S-T, E-S-T, E-T, M-S-T, E-M, E-S, M-S, S-T. The results for the different types of integration varied considerably. Integrating the four disciplines, E-M-S-T, showed a large effect size (1.76), whilst the effect size for integrating engineering and mathematics (E-M) was small (0.03). Also low was the effect size for mathematics (0.23) when integrating mathematics, science, and technology (M-S-T). A study that integrated technology and science in high school had a very large effect size (2.80). Becker and Park suggest that "the types of integration may be the key factor that impact the effects of the integrative approaches among STEM subjects" (p. 31).

Unsurprisingly, Becker and Park (2014) found the effect size for the primary years was greater than in the secondary and college years. The flexible school and classroom structures in the primary years facilitate the implementation of integrative approaches and according to Sanders (2009), teachers should take advantage of the unique opportunity offered to stimulate students' interest in STEM as early in their education as possible. Becker and Park do not go on to elaborate on why the effect sizes for mathematics were low in the integrative STEM studies. This leaves the reasons for the low results open to speculation. Among other reasons, low results may be due to the lack of teacher content knowledge (Treacy & O'Donoghue, 2014) or due to a lack of focus on the mathematics (Schmidt & Houang, 2007).

Becker and Park's (2014) results are offered with a note of caution. They admit that the number of studies included in their study is considered low for a meta-analysis. The extensive search they undertook revealed that many studies did not report on the mathematics achievement of students. For example, a study of K-5 students conducted by Hefty (2015) describes a school program that implemented tasks that focused on the engineering design process. The author highlights the mathematics outcomes targeted in each activity, such as measurement of height and angles in the *Laser Light Maze* activity, but does not detail the specific curriculum outcomes addressed nor does he report on the students' achievement according to those mathematics outcomes. Hefty reports learning gains in mathematics achievement that exceed the district and state averages but does not go as far as providing specific details about that achievement or how the results were determined. He also reports that "teachers notice carryover from engineering to mathematics lessons" (p. 427). This implies the students gain a lot from the activities but to be convincing that an engineering design integrative approach in STEM education is going to impact positively on the learning of mathematics outcomes, more evidence is required.

What are the Implications for the Learning and Teaching of Mathematics?

The implementation of an integrated STEM education raises many challenges for the teaching and learning of mathematics but "transforming the current educational paradigm toward a STEM education perspective" (Breiner et al., 2012, p. 3) has the potential to "foster the connectedness that reflects the way the world works outside of school and assist students to develop the knowledge and ability to deal with change and challenge in sensible ways" (Rennie, Wallace et al., 2012, p. 1). There does not, however, appear to be one teaching approach established for the implementation of STEM education (Berry et al., 2012; Herschbach, 2011; Rennie, Venville, & Wallace, 2012) that will optimise the opportunities for students to develop the STEM skills proposed by Sneider and Purzer

(2014). The individual disciplines do, however, have dominant practices that complement the implementation of STEM education. Those practices include problem-based learning, project-based learning, scientific inquiry, and engineering design (Rennie, Venville et al., 2012). Research has focused on these discipline practices (e.g., English, Dawes, & Hudson, 2013; Moore et al., 2014; Rennie, Venville et al., 2012) but noticeably absent from the literature is the conceptualisation of mathematics practices and concepts that have the potential to contribute to the understanding of other disciplines (Rennie, Venville et al., 2012).

Although the connectedness and applicability of mathematics to real-world contexts and across disciplines is fostered when integrative approaches are adopted (Berry et al., 2012) the implementation of these approaches has the potential to disrupt the coherence of mathematics learning programs (Schmidt & Houang, 2007). Schmidt and Houang contend that coherence in the delivery of the mathematics curriculum is critical when seeking to improve the student achievement. Their view of coherence was determined from an analysis of the Third International Mathematics and Science Study conducted in 1997. Coherence is present when the content covered increases in complexity from simple mathematics and routine computational procedures with fractions, say, to deeper structures, such as understanding the rational number system and its properties. This development occurs both over time within a particular grade level as concepts and ideas are introduced for the first time, and then are built upon through the years as students progress across grades (Schmidt & Houang). This implies that both coverage of the content and depth of understanding are the focus of learning opportunities.

What Does Mathematics Have to Offer STEM?

According to Shaughnessy (2013), “the M will become silent if not given significant attention” (p. 324) when implementing integrative STEM education programs. The difficulty of improving outcomes in mathematics when implementing integrative approaches (Becker & Park, 2014) warrants particular consideration, especially in relation to the coherence and coverage of the mathematics curriculum (Schmidt & Houang, 2007).

It is not uncommon to find in the literature reports that suggest STEM education learning opportunities provide the context for enhancing the development of mathematical skills (e.g., Alfieri, Higashi, Shoop, & Schunn, 2015; Hefty, 2015; Magiera, 2013; Smith et al., 2013). These examples, however, do not acknowledge the reciprocal nature of the relationship between mathematics and STEM. They provide examples of STEM education opportunities that support the development of mathematical ideas and concepts but do not exemplify the way in which mathematics can influence and contribute to the understanding of the ideas and concepts of other STEM disciplines.

In some cases, the mathematics is incidental to the purpose of activities. For example, an activity that requires students to explore the characteristics of aluminium baseball bats to develop an understanding of the denting strength of the bats was designed to support students’ development of problem solving skills (Magiera, 2013). The mathematics of measures of centre was applied to determine the average size of aluminium crystals on the surface of baseball bats. In this example, the mathematics was not pivotal to the success of the activity but contributed to the outcomes identified. The activity did not extend to using or developing the proportional reasoning skills needed to understand the concept of density that is directly related to the strength of the bats.

Alfieri et al. (2015) also describe a proportional reasoning activity suitable for middle school students where the mathematics is incidental to the STEM context. They use the context of an animated robotics game, *Expedition Atlantis*, to provide situations where proportional reasoning calculations are made. For example, students calculate how many times the wheel of an underwater robotic device need to turn in order to move a particular distance. Although robotics is a common STEM context where mathematics is used to develop students' understanding of how to manipulate and move machines (e.g., Allen, 2013; Silk, Higashi, Shoop, & Schunn, 2010), in this case, the context of robotics is used to motivate students to make practice the mathematical procedures targeted.

Another activity, *Exploring Slope with Stairs and Steps* (Smith et al., 2013), utilised mathematics in an instrumental way. This activity involved using rates of change to develop an understanding of the concepts of slope and steepness within an engineering context. In this case, the mathematics associated with rates of change was pivotal to the understanding of the construction of stairs, which also applies to other STEM contexts, such as road construction and the safe descent of vehicles down a hill. Another activity where the mathematics is instrumental to student understanding of the concepts involved in a STEM context is related to the sale of muffins (Baron, 2015). The author states, "Selling muffins introduced the students to quadratic functions" (p. 335) and described the way in which using functions in this context provided the opportunity to review the vocabulary of functions encountered previously, such as coefficient, variable, and exponent. Baron's aim was to use relevant contexts to apply and model quadratic functions. What difference would it make if the teacher's purpose were to use quadratics and functions to make decisions about selling muffins and what would be the role of the mathematics in that scenario?

Silk et al. (2010) suggest that making subtle changes in the design and setup of lessons makes a substantive difference in what students learn. This is demonstrated in their activity that required students to synchronise the movements of robots when dancing. Originally, the activity was designed to get students "to make a dance routine that would incorporate a range of different moves (at different distances, angles, and speeds) and a range of different size robots (that varied on their wheel size and track width)" (p. 25). The project team expected students to generalise their understanding of proportional reasoning to solve the problem. They found that the majority of students used guess-and-check strategies to continually tweak the parameters in their programs until the robots looked synchronised with each other. It was not until Silk et al. made the role of the mathematics in the activity explicit to the students through the redesign of the activity that the students were able to use the mathematics purposefully and connect with the underlying general relationships associated with making the robots move synchronously.

Conclusion

Mathematics is often mentioned as underpinning the other disciplines of STEM because it serves as a language for science, engineering, and technology (Schmidt & Houang, 2007). Is that sufficient acknowledgement of the potential role of mathematics in STEM learning contexts? Stating that mathematics underpins the other disciplines sets mathematics up in a supporting role in integrative STEM education contexts. Ideally, mathematics should be given more standing and be considered an enabler or imperative for the advancement of understanding of concepts in other disciplines. Silk and his colleagues suggest, "One way to do this is to repeatedly foreground" the desired [mathematical] content while temporarily pushing other concepts into the background" (p. 23). A shift in focus from the incidental nature of mathematics in learning activities to a focus on the instrumental nature of the mathematics may be one way of making the mathematics more explicit within STEM learning contexts and activities. Research is required to determine which integrative approaches put mathematics most effectively to the forefront of learning experiences.

In Australia, the push for improved STEM education outcomes comes at a time when there is no integrative STEM curriculum to support its implementation into learning programs. Fortunately, the Australian Curriculum also includes the General Capabilities, which embody the learning, literacy, and life skills considered to be 21st century skills (ACARA, 2015; Bowman, 2010). Incorporating explicit teaching of the capabilities within integrative STEM contexts has the potential to enhance further the outcomes from learning activities. Although structured in disciplines, integration of the Australian Curriculum is possible by addressing the General Capabilities in learning activities across the curriculum together with additional STEM content outcomes. Such an approach is achievable within the school and classroom structures that are dominant in Australia. How this impacts on student learning of the key concepts in mathematics and the other disciplines warrants further research.

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