Chapter 3
STEM Education for the Twenty-First Century

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3.1 What Is STEM?

The acronym STEM (Science, Technology, Engineering, and Mathematics) has become increasingly important in policy advocacy across the world, in relation to industry and research, to higher education participation, and to school curricula (Marginson, Tytler, Freeman, & Roberts, 2013). STEM education and research are increasingly recognized as fundamental drivers of national development, economic productivity, and societal well-being. Yet, the particular juxtaposition of these subjects is only recent, is not universal, and is in many respects contested. The acronym was coined by Dr Judith Ramaley in 2001, then assistant director of the human resources directorate at the US National Science Foundation. She is quoted as saying (Chute, 2009):

> It is impossible to make wise personal decisions or to exercise good citizenship or compete in an increasingly global economy or to begin to address the enormous challenges we face in exercising our stewardship of our environment without knowledge of science and the ability to apply that knowledge thoughtfully and appropriately.

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This quote picks up some of the key constructs underpinning STEM advocacy: that of the need for STEM knowledge and skills in a contemporary world, the demands of a global economy, and the challenges of an increasingly threatened environment.

Underpinning the acronym is the notion that these four disciplines together constitute a coherent package of subjects that cover the knowledge and skills around the sciences, applied sciences, and the digital world that constitute the driving force towards a post-industrial global future and the future wealth of countries. Yet, the term is not precise in its meaning. The original acronym was SMET, with science and mathematics taking pride of place, but Ramaley's conception was of a more meaningful connection amongst these disciplines. Thus, we see early on the introduction of the suggestion that STEM amounts to more than the sum of its disciplinary parts. The US STEM School Education Strategy report (Education Council, 2015) argues that the four elements work together as a united concept by virtue of their intersecting use. For instance, the engineering design process is informed by scientific empirical evidence (Honey, Pearson, & Schweingruber, 2014). The American National Science Foundation (NSF) also reports STEM as a way to encompass a new "meta-discipline" that combines the four subject areas. Nevertheless, as we will explore below, questions are raised about the epistemic viability of the STEM construct.

There is imprecision in the disciplinary makeup of STEM (Marginson et al., 2013). For instance, in reporting on STEM participation or economic figures, the term sometimes includes the health sciences and medicine, and sometimes agriculture (some have advocated an extension of the acronym to STEMM, or STEAM, on this basis) and sometimes not. In Germany, the acronym is MINT (*Mathematik*, *Informatik*, *Naturwissenschaft* und *Technik)*, which makes apparent the inclusion of information technologies, whereas in the English-speaking versions, in schools, Technology ambiguously encompasses both design and information technology.

In school curricula, the acronym has largely focused on mathematics and science, these being the major high-status disciplinary subjects, with engineering education in academic streams struggling to achieve the attention implied by the acronym (English, 2016). Historically, there has been longstanding advocacy of the inclusion of technology within school science (namely, in the Science-Technology-Society movement: Fensham, 1981, 1985; Yager, 1996), yet the T in STEM is increasingly associated with digital technologies as the fourth industrial revolution, built on artificial intelligence, machine learning, and big data processes, takes hold of both industrial organization, work realities, and personal lives. Correspondingly, the meaning of STEM in education has a variety of forms internationally, including:

- An emphasis on promotion of mathematics and science as a response to perceptions that these subjects are attracting less student interest and participation (Marginson et al., 2013)
- Promotion of engineering design curricula allied with mathematics and science, for instance, as part of the Crosscutting Concepts in the US Next Generation Science Standards (NRC, 2012)

- Promotion of the inclusion of digital technologies either as a standalone subject or infused throughout the curriculum
- Interdisciplinary project work or subjects that combine two or more of the STEM disciplines, grounded in ‘authentic’ contexts and focused on problem solving (Tytler, Swanson, & Appelbaum, 2015)
- Increased curricular emphasis on the world of STEM professional work, including partnerships or links with STEM industries and professional practices in Australia (Australian Education Council, 2018) and the UK (Mann & Oldknow, 2012) or the Siemens-Siftung ‘Experimento’ in Germany
- The combination of the STEM disciplines with ‘Arts’ in ‘STEAM’ initiatives that emphasize creativity and design thinking (Taylor, 2016). These initiatives are linked to an emphasis on innovation as a core industrial wealth-building practice and
- Increasing curricular emphasis on ‘STEM skills’, aligned with concerns to prepare students for a fast-changing world of work in the twenty-first century (Prinsley & Baranyai, 2015; UK National Audit Office, 2018).

Internationally, governments around the world are focused on enhancing their citizens’ STEM capabilities. The Australian Government funded *STEM: Country Comparisons* project (Freeman, Marginson, & Tytler, 2015; Marginson et al., 2013) commissioned 23 country reports that investigated, among other things, patterns of STEM provision in school and tertiary education, student uptake of STEM programs, factors affecting student performance and motivation, and strategies and programs to enhance STEM. Country and regional reports spanned Europe (Western Europe, Finland, France, Portugal, Russia), the Anglosphere (United States, Canada, New Zealand, United Kingdom, Australia), Asia (China, Taiwan, Japan, Singapore, South Korea), Latin America (Argentina, Brazil), the Middle East (Israel), and South Africa. The consensus of all the country chapters is that it is essential to foster scientific and mathematical literacy in all students to middle school level; it is desirable to persuade all students to maintain some STEM programs for as long as possible; and more students should be persuaded to aspire to STEM learning and STEM-based careers.

These latter aims respond to a substantial literature in each of mathematics and science education concerning the factors that affect student attitudes and perceptions to these subjects, and intentions to continue in a ‘STEM pipeline’ to post compulsory school mathematics and science, and further tertiary STEM studies. In a comprehensive review, Tytler, Osborne, Williams, Tytler, and Cripps Clark (2008) identified a complex array of intersecting factors that differed at different points along the education pathway from primary school through to upper secondary school. These factors include experience of success or otherwise, and students’ attitudes, particularly interest and self-efficacy, determined by a range of cultural factors including socio-economic, teaching and teachers, patterns of choice and knowledge and expectations of future pathways.

3.2 Drivers for the Contemporary Focus on STEM Education

The arguments for the global turn to STEM in education and in research and development, common across both industrialized and developing countries, are well rehearsed and widely recognized (Freeman et al., 2015; Marginson et al., 2013). The turn to STEM is clearly evident in government efforts worldwide to elaborate policy regarding school mathematics and science, and tertiary level education and research in the STEM disciplines. The argument for this increasing focus on STEM is based on claims of the centrality of STEM knowledge and skills, and STEM-based innovation, to national wealth creation. The case has been argued, for instance, in a series of major policy documents in the industrialized world (COSEPUP, 2006; HLG, 2004; Office of the Chief Scientist, 2013, 2014) and, in these cases, is accompanied by a sense of crisis concerning a perceived drop in participation of youth in the 'STEM pipeline' (e.g. Osborne & Dillon, 2008; Tytler, 2007; Tytler et al., 2008) towards post-compulsory STEM studies and employment, and an impending shortfall in the STEM professional workforce perceived of as central to global economic competitiveness. The focus on STEM education relates to the demonstrable links between countries' education attainment (increasingly perceived in global terms through comparative assessment regimes such as PISA and TIMSS), science research and development programs, and economic dynamism.

> In governments around the world it is believed there is a relationship between, on the one hand, national investment in STEM-related skills, and the quality and quantity of the national skill base, and, on the other hand, the economic productivity of the workforce … and research-based innovations in industry. There is no contemporary nation with an economy both vigorous and well-integrated that is not also strong in STEM (Freeman et al., 2015, p. 1)

The move to centralize STEM in schools is premised on the argument that success in STEM within schools, increasingly linked to performance on national curricular assessment regimes, is a core determinant of a nation state's future international economic competitiveness and a necessary driver for economic growth. Figure 3.1 represents the presumed interactive relationship between STEM national educational attainment, health of STEM research and development, and the economic dynamism of the nation.

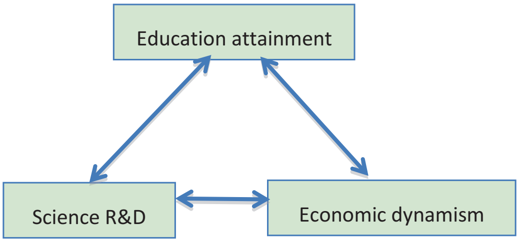

Fig. 3.1 The interactive relationship between national educational attainment, health of STEM research and development, and economic dynamism

In this way, the STEM acronym has represented more than a set of academic subjects, but as a distinctive discourse serving an agenda of globalizing economic modernization within the New Knowledge Economy. Further, the acronym serves to provide a distinction between the STEM disciplines and those of the Arts, Humanities, and Social Sciences.

3.2.1 The STEM Workforce

This tight linking of STEM advocacy with national economic well-being is driven by recognition of the increasing importance of the STEM disciplines in the workforce. For example, in Australia, it is claimed that 75% of the fastest growing occupations require STEM skills (Office of the Chief Scientist, 2014). It is estimated that shifting just 1% of the workforce into STEM roles would add $57 billion to GDP over 20 years (PwC Australia, 2015).

> The (STEM) fields and those who work in them are critical engines of innovation and growth: according to one recent estimate, while only about five percent of the U.S. workforce is employed in STEM fields, the STEM workforce accounts for more than fifty percent of the nation's sustained economic growth (Office of the Chief Scientist, 2014)

It is claimed (Institute of Mechanical Engineers, 2018), based on a survey of business leaders in the UK, that lack of STEM skills costs that country £1.5bn each year. Most of the fastest growing occupations in the US are predicted to be in STEM, particularly in health and computing (Lacey & Wright, 2009). In the US, it is claimed (Olson & Riordan, 2012) that the US must produce approximately 1 million more STEM professionals over the next decade than are projected to graduate at current rates (an estimated increase of about 34% annually) if the country is to retain its historical pre-eminence in science and technology. Concern with supply of engineering graduates is well established in the US, for instance, in talk of a 'gathering storm' in the COSEPUP (2006) report about the relative proportional number of engineers graduating from the US compared to China, which, at the time, was less than 1:8.

Nevertheless, questions have been raised about the veracity of these estimates. Oleson, Hora, and Benbow (2014) point out that estimates of STEM jobs differ widely, depending on assumptions embedded in the acronym. Further, there is acknowledgement that despite these calls for more STEM graduates, many graduates from the STEM disciplines fail to get jobs in their chosen fields and end up working in professions only indirectly related to their degree. There is growing recognition of the complexity of the STEM construct in future work predictions, particularly around the distinction between STEM competencies distinct from STEM professions. It has been argued for instance with reference to the US that "STEM jobs account for about 5 percent of all jobs in the economy. STEM competencies, however, valued outside of traditional STEM jobs – account for 40 percent of all jobs" (Carnevale, quoted in Sarachan, 2013). A recent US report (National

Science Board, 2015) has questioned presumptions of a linear link between a 'STEM pipeline' and STEM professions, and argued for a more nuanced consideration of STEM pathways to "foster a strong, STEM-capable workforce" (p. 2) conceived of more flexibly. Thus, recent concern has shifted from a focus on the need for STEM professionals, to a focus on the building within the workforce of STEM skills or competencies (Marginson et al., 2013).

3.3 Work Futures and STEM Competencies

The world of work is undergoing dramatic change, causing significant disruption in patterns of jobs, and changing the nature of expectations of the young people currently in our schooling systems, as to what their career futures might look like. Increasingly, young people are experiencing significant change away from the settled careers expected by previous generations.

> A 15-year-old today will experience a portfolio career, potentially having 17 different jobs over five careers in their lifetime" (FYA, 2017, p. 3)

The major drivers for these changes are largely agreed. How we work is being impacted by mega-trends, including "globalisation, technological progress and demographic change" (OECD, 2017, p. 2). The key sites for technological progress are in "Big Data, artificial intelligence (AI), the Internet of Things and ever-increasing computing power" (p. 4). Added to this are the substantial natural world and social drivers of climate change, globalization, urbanization, population pressures, and changed demographic profiles, with an aging population in industrialized countries leading to substantial pressures on wealth creation and health provision.

The effect of this fourth industrial revolution (Schwab, 2016) is already being felt in a shift from manufacturing and the loss of many repetitive jobs to machines. In the coming years, digitization will increasingly encroach on professional work previously presumed to be impervious to machine replacement, such as accountancy and office work generally. High status STEM professions will change due to big data processes and automation, such as diagnosis processes in medicine, or data analysis and display and virtual reality-supported design procedures in engineering. These changes will be fundamental and disruptive and may have profound implications for the conduct of schooling. Already, STEM subjects in schools are increasingly taking on digitization as a key aspect of teaching and learning. The explosion of information access and organization through the internet has posed profound questions on the position of schooled knowledge and the relationship between declarative knowledge, critical thinking, and higher-level skills.

A recent and major study of work futures in Australia (Hajkowicz et al., 2016) identified 'new skills and mindsets' that will be needed for the future, including: increasing importance of education and training; the importance of digital literacy alongside literacy and numeracy; new capabilities to match new jobs; and, increased importance of STEM knowledge and skills. This latter is linked to the STEM-related sector as having the biggest increases in job numbers and wages.

> The current education system teaches people to be effective in a highly structured system, but Australia's future workforce is likely to encounter much ambiguity and openness. For this reason, commentators argue that our future educational system will need to do more to encourage innovative, entrepreneurial and flexible mindsets (Hajkowicz et al., 2016, p. 87)

Writers in this area of work futures are agreed that youth, in preparing for this fast-changing future of work, need to develop new skills that include problem solving, fluency and active learning (Bakhshi, Downing, Osborne, & Schneider, 2017), adaptability and creativity, interpersonal skills, and transdisciplinary skills (Tytler et al., 2019). There is increasing emphasis on the notion of twenty-first century skills as a focus for education, which will prepare students for these volatile work futures (Binkley et al., 2012). Andreas Schleicher, OECD Director of Education and Skills, argued in the 2017 OECD forum:

> What is required is the capacity to think across disciplines, connect ideas and construct information: these global competencies will shape our world and the way we work and live together.

These imperatives regarding the new realities of work and life are driving increasing advocacy of competency-based curriculum framing, and a corresponding framing of STEM education in terms of STEM skills, as distinct from disciplinary knowledge in the traditional sense, as a crucial component of twenty-first century skills. But, while the phrase 'STEM skills' is often used in public advocacy of STEM, the term is not well defined. In Australia, the Office of the Chief Scientist (Prinsley & Baranyai, 2015) reported on an investigation of the skills and attributes employers look for in STEM graduates. The top five skills were active learning (on the job), critical thinking, complex problem-solving, creative problem-solving, and interpersonal skills. Occupation-specific STEM skills came down the list at number 8. All but the last of these five was held to be more characteristic of STEM, compared to non-STEM employees.

Drawing on an analysis of Carnevale and colleagues, the National Science Board (2015) talked about 'STEM capabilities' thus:

> Among the cognitive competencies associated with STEM are knowledge of math, chemistry, and other scientific and engineering fields; STEM skills, such as complex problem solving, technology design, and programming; and STEM abilities, including deductive and inductive reasoning, mathematical reasoning, and facility with numbers. Among the non-cognitive competencies associated with STEM are preferences for investigative and independent work (p. 8)

Siekmann and Korbel (2016), in a review of the STEM skills literature, argue that the term is not appropriate for many of the competencies claimed in that these refer to skills that can be developed equally through non-STEM disciplines. They argue that "current definitions of STEM skills are inconsistent and not specific enough to inform education and skill policies and initiatives" (p. 8), and put the case that the term should be restricted to specific technical skills. Their analysis draws attention to the different ways in which we can think of STEM curricula contributing to competencies for the workforce or for living, including; (a) specific STEM knowledge and skills and particular forms of reasoning; (b) competencies particularly but not exclusively associated with STEM (such as critical and creative thinking); and (c) general competencies (such as collaborative or communicative skills) that could be productively developed in STEM contexts.

Table 3.1, based on the OECD Learning Framework 2030 (OECD, 2018), presents a framework for thinking about skills needed by young people to prepare them for future life and work, with descriptors that aim to articulate the contribution of STEM subjects to the development of these skills.

The knowledges, skills, attitudes, and values of Table 3.1 are well aligned with findings and advocacy within the research literature in mathematics and science education, but with the exception of disciplinary knowledge, and arguably procedural knowledge, have not found their way into formulations of mainstream curriculum practice or assessment. STEM advocacy around skills for future work, however, has given them renewed prominence. These skills and attitudes can be seen in the OECD Mathematics Competencies Framework 2030, for instance, in the attention to mathematics use across multiple contexts, or in categories, such as creative problem solving, critical thinking, inquiry, resilience, design thinking.

Epistemic knowledge is a category within the 2015 Scientific literacy framework, and refers to knowledge of the constructs and defining features of knowledge-building in science (Duschl, 2008), including the way evidence is used to test and

Table 3.1 A framework of competencies associated with the STEM disciplines, based on the OECD Learning Framework 2030

Knowledge	
Disciplinary knowledge	Concepts such as energy, geometric relations, material and structural properties, ecosystem principles …
Epistemic knowledge	How knowledge is built in the STEM disciplines, social and personal settings of STEM knowledge building, nature of models in maths and science, design processes, algorithmic coding processes …
Interdisciplinary knowledge	Interdisciplinary processes, links between mathematics and science, technology, STEM and other knowledges- societal, humanities and arts …
Procedural knowledge	Investigative and problem-solving approaches, design knowledge, coding knowledge …
Skills	
Cognitive/ metacognitive	Complex and creative problem solving, design thinking, critical thinking, systems analysis, computational skills, complex, model based reasoning …
Social/	Interpersonal skills, cooperation/ collaboration, …
Physical/practical	Technical skills, coding, manipulation …
Attitudes	Productive disposition, persistence and optimism, curiosity, aesthetic preferences, open mindedness, respect for evidence, commitment to learning …
Values	Care for animals, objectivity, cooperation, responsibility … (Personal-global)

establish claims, and the nature and role of models and representations in scientific discovery and explanatory processes. Similarly, in mathematics, epistemic knowledge includes understanding of the nature of mathematical knowledge-building, proof, and including the role of representational systems (Lehrer, 2009; Lehrer, Kim, & Schauble, 2007). Lehrer and Schauble (2012), over a decade long program of research, have worked with young children to develop and refine representational systems in response to genuine exploration of natural systems, including the construction, interrogation, and modelling of data sets. In science, such representational work underpins inquiry pedagogies focusing on multimodal representational work (Hand, McDermott, & Prain, 2016; Lehrer, 2009; Tytler, Prain, Hubber, & Waldrip, 2013), visualization (Gilbert, 2005), and metarepresentational competence (diSessa, 2004). Epistemic knowledge also underpins the literature on the nature of science (Lederman, 2014), and argumentation (Simon, Erduran, & Osborne, 2006), where it is held to be a crucial aspect of scientific literacy to understand the processes by which scientific knowledge is built on evidence, in an age, where science findings are increasingly subject to political critique. Consideration of epistemology and epistemic processes has a long history also in mathematics education (Ernest, 2003).

Further, epistemic knowledge also includes knowledge of the personal and social drivers of STEM discovery and development processes, and the ways in which STEM practitioners operate in a variety of professional and practical settings. Again, this aspect of epistemic knowledge is aligned with calls for the school STEM subjects to better reflect practices in the STEM professions, to offer exposure to STEM practices, and to encourage partnerships between schools and STEM industries and STEM practitioners. This call underpins, for example, the UK STEMNET Ambassadors initiative (https://www.stem.org.uk/stem-ambassadors), the Siemens Siftung initiative (https://www.siemens-stiftung.org/en/foundation/working-areas/education/), and the Australian STEM professionals in schools initiative (Tytler et al., 2015). For mathematics education in particular, there is a disparity between the formal curriculum and the diverse ways in which mathematics is created and used in multiple professional settings such that the link between mathematics and what is a ‘mathematician’ is much less clearly defined or understood than the link between school science and perceptions of a ‘scientist’. This represents a dual challenge for mathematics education within a STEM setting: to develop a mathematical literacy perspective that encompasses a rich view of mathematical epistemic practices and to represent the diverse professional settings in which mathematics is created and used, aligned with the need to alert students to the centrality of mathematics to multiple possible work futures.

Interdisciplinary knowledge has not been an explicit focus for mathematics and science in schools. However, science, along with other subjects, utilizes mathematics as a tool for many purposes, and mathematics, in applied topics especially, uses science for context. Similarly, technology/engineering design projects draw on both mathematics and science as part of the design and evaluation process, but, typically, the science and the mathematics are not developed beyond their immediate utilitarian value. However, there is a growing argument that interdisciplinary thinking and practice is a core feature of contemporary STEM professional work, and that innovation occurs mostly at the intersection of disciplinary practices. This implies a need to explore ways of developing serious learning approaches in mathematics and science within interdisciplinary settings. How this might be done, and the challenges involved, will be discussed in the next section.

Further to advocacy for STEM, in a number of systems around the world, the acronym STEAM, with the A being for 'Arts', is achieving curriculum currency as an expanded form of interdisciplinarity. In Korea, for instance, there has been major system innovation around STEAM, with an emphasis on creativity and innovation (Baek et al., 2011; Jon & Chung, 2015). In China also, there is significant curricular activity around the STEAM concept. The term originated in the U.S., but is gaining increasing currency globally around this association with creative thinking and innovation (Taylor, 2016), which has garnered support from industries who see innovation and design as central to their STEM practices. STEM teachers working with arts teachers, around more flexible pedagogies, have seen the association as powerful for increasing student engagement with mathematics and science.

Cognitive/metacognitive skills. As was described above, industry and government are looking to STEM education as a principal training ground for the development of skills of complex and creative problem solving, critical thinking, and analytic and quantitative thinking, all highly valued as workforce skills. This places, therefore, a premium, for STEM curriculum framing, on these cognitive/metacognitive skills. Since the turn of the century, Scientific Literacy (Bybee, 1997) has been argued to be a core purpose of school science curricula, emphasizing the importance of preparing future citizens for being able to interpret and use scientific knowledge and processes in their everyday lives. This focus constitutes an implicit critique of the traditional purpose ascribed to science education, of preparing a core of students as future STEM professionals. As with Scientific Literacy, Mathematical Literacy has underpinned the PISA mathematics framework. Similarly, the construct of numeracy "connects the mathematics learned at school with out-of-school situations that additionally require problem solving, critical judgment, and making sense of non-mathematical context" (Goos, 2016, p. 71). The PISA framework has been structured around competencies, recognizing that what is important, as the result of an education in mathematics, science, or any discipline, is the capacity to turn discipline-based knowledge to use in interpreting and solving questions and problems. This move towards 'knowledge in use' and away from declarative or lower level conceptual knowledge has been aligned both with a concern for a STEM education that prepares all citizens for future lives, but, more recently, with a concern to foster the flexible sets of skills and competencies that will be increasingly important in future workplaces.

Attitudes and values are increasingly recognized as an important component of learning and are an important dimension in understanding the conditions for students' ongoing engagement with STEM subjects. In the next section, the perceived importance of attitude and engagement responses to mathematics is identified as an important driver for schools' interdisciplinary work. Values both frame students' responses to STEM subjects and are promoted within these subjects (Bishop, Seah, & Chin, 2003; Schreiner & Sjøberg, 2007). Regarding attitudes in the science education literature, an important distinction is made between 'attitudes towards science' and 'scientific attitudes' (Tytler & Osborne, 2012). The latter are envisaged as a component of working and thinking scientifically and include such things as a commitment to evidence as the basis of belief, and a scepticism towards hypotheses and claims. The distinction also holds true for mathematics and could be applied also to 'values'. Attitudes include broad orientations to working within a subject, such as resilience and optimism, which are important facets of deeper level mathematical learning and ways of knowing (Williams, 2002, 2014). In mathematics, productive disposition "includes the student's habitual inclination to see mathematics as a sensible, useful, and worthwhile subject to be learned, coupled with a belief in the value of diligent work and in one's own efficacy as a doer of mathematics" (Kilpatrick, 2001, p. 107). This competency is framed as important for the learning of mathematics (or science), but is also essential for any ongoing tendency to seek out or use school STEM knowledge in adult life or work.

A particularly productive link between conceptual learning and attitudes and values was articulated by John Dewey (1996) as a continuity between conceptual learning and the aesthetic. This idea has been explored in the work of mathematicians (Netz, 2005), scientists (Wickmann, 2006), in mathematics classrooms (Sinclair, 2009), and in science classrooms (Jakobson & Wickman, 2008), where aesthetic expression is shown to intertwine with conceptual statements, as students interact with material objects and scientific practices.

3.4 The Move Towards Interdisciplinarity

The STEM acronym, originally coined to represent an interrelated grouping of disciplines and school and tertiary level subjects, has shifted towards advocacy of interdisciplinary curriculum practices built around authentic problems, involving some or all of science, technology, engineering, and mathematics. This shift occurred early in the US, but, in recent years, has become a feature of global STEM curriculum advocacy (Marginson et al., 2013). A key aspect of the argument for interdisciplinary approaches to STEM is the call for students to be engaged with authentic problems that reflect the interdisciplinary nature of much contemporary STEM work. Often, these activities involve project-based learning and, often, these are based around engineering/technology design challenges. Part of the argument for authentic problem contexts lies in the concern about lack of conceptual engagement of many students with school science and mathematics, described above, and the premise that work around authentic contexts will lead to more meaningful learning. Another part of the argument is that interdisciplinary contexts and project-based learning can more effectively provide the settings for developing the STEM skills of critical thinking, creative problem-solving, innovation, and collaborative team work, than prevailing curriculum/pedagogical traditions in school mathematics and science. Such interdisciplinary work is held to bring school STEM activities closer to the way these are practised in real world STEM. The move towards interdisciplinary STEM is thus justified through arguments of authenticity, engagement, and open pedagogies supporting STEM skills.

There is some confusion, however, about what interdisciplinary STEM in schools should look like. Bybee (2013) described a variety of arrangements for implementing interdisciplinary STEM curricula, pointing to a state of relative confusion as to what might prove a productive approach. There are a variety of accounts of how relations between contributing STEM subjects might be conceptualized in this work. Vasquez (2015) describes these as disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary. Samuels (2009, p. 49) describes multidisciplinarity as the sharing of individual knowledge by experts, interdisciplinarity as the creation of knowledge "at the intersection of established disciplines", and transdisciplinarity as the creation of new knowledge stemming from "the interaction of diverse people within an entirely new group". The distinction between these terms is hard to decipher in the details of how teachers and ideas and activities might interact in a school setting, but, essentially, the difference lies in the extent to which new 'meta-knowledge' is produced that is more than the sum of the parts of the disciplinary knowledge and the extent to which members of an interdisciplinary team form a coherent group around ideas that transcend their individual disciplinary knowledges. We have argued elsewhere (Tytler, Prain, & Hobbs, 2019) that part of the problem in characterizing such interdisciplinary activity lies with the spatial metaphor through which the interactions across boundaries are described, which leaves untouched the short- and longer-term temporal relations concerning the way disciplinary knowledges are conscripted to a task.

Indeed, there have been serious questions raised about the epistemic basis on which the STEM subjects are imagined to interact and about the capacity of interdisciplinary STEM activity to support significant learning in mathematics and science. Clarke (2014) points to the very different epistemic practices that constitute the four STEM disciplines, in terms of the relations between truth claims and evidence and the nature of the evidence, the discursive practices through which knowledge is built and the tools used. He characterizes interdisciplinary STEM as a possibly 'monumental category error'. Lehrer (2016, 2017) argues that many integrated STEM projects, while engaging for students, fail to engage students in deeper disciplinary practices and fail to present a curriculum agenda that would represent a coherent knowledge progression. A major review of integrated STEM curricula in the US (Honey et al., 2014) found that, while these activities improved student attitudes, there was little evidence of improved learning, especially for mathematics. There was a general concern about the level of mathematical thinking represented in these projects. They nevertheless argue the potential of integrated approaches, alongside maintaining a focus on the individual subjects.

There seem to be two related problems particular to mathematics learning through interdisciplinary design tasks. First, mathematics often plays a service role, involving already known mathematics as a tool, for instance, through calculations or graphical representation, without regard for the development of new mathematical insights through students making mathematical decisions as part of a challenging, unfamiliar problem (Barnes, 2000). Second, the highly structured nature of the school mathematics curriculum, compared to science or technology, for instance, makes it difficult to accommodate such interdisciplinary tasks as a significant contribution to the curriculum as it currently stands.

Williams et al. (2016), in their review of interdisciplinarity in Mathematics Education, argue that disciplines are defined through historically and culturally contextualized social practices supported by a variety of structures that constrain discourse and allow efficient communication in disciplinary group processes. They make the point that disciplinary thinking does not exist in pure form and that mathematicians will inevitably draw on other-than-abstracted mathematical thinking in their activity. They argue that "interdisciplinary mathematics education offers mathematics to the wider world in the form of added value (e.g. in problem solving), but on the other hand also offers to mathematics the added value of the wider world" (p. 13). By implication, therefore, school mathematics learning can be advantaged from opening up to interdisciplinary curricular practices.

In a review of studies of interdisciplinary mathematics education, Williams et al. (2016) drew on a number of previous meta analyses and reviews. For instance, they refer to a 28-study meta-analysis of Becker and Park (2011) which concluded that:

> integration at elementary level has the largest effect, as does integrating all four S, T, E and M. They also found that the positive effects of integration were the smallest in relation to mathematics achievement, but argue that the increased student interest in the subject due to seeing its real-world connections, may lay the basis for improved achievement in the longer term (Williams et al., 2016, p. 16)

Williams et al.'s review offered a number of significant findings for interdisciplinary mathematics education. First, they make the point that, despite it having been advocated and explored in curricular practice for many years, this field of research is relatively underdeveloped in that in the existing studies there is "wide variation in who is measured (teachers or students …); the nature of the interdisciplinarity involved … ; how integrated that interdisciplinarity is; the nature and fidelity of the intervention; which outcomes are being measured; how these outcomes are measured and how they are analysed" (p. 19). Second, they concluded: "there is evidence of learning gains from integrated curricular and interdisciplinary working, mainly for learning outcomes of affect, of problem-solving processes, and of metadisciplinarity" (p. 17). Third, they point out that these gains are non-traditional and non-standard and that integration is thus likely to be rejected in systems that value only traditional measures.

The history of integrated studies indicates a difficulty in their establishment within a culture of school teaching and learning strongly focused around high status discipline-based subjects (Venville, Wallace, Rennie, & Malone, 1998). Venville, Rennie, and Wallace (2012, p. 737) list a range of barriers to subject integration as envisaged in STEM, including "subject matter knowledge, pedagogical content knowledge and beliefs … instructional practices … administrative policies, curriculum and testing constraints … school traditions … school organization, classroom structure, timetable, teacher qualifications, collaborative planning time and approach to assessment". Williams et al. (2016), in their review, argue the need for investment in development, support, and infrastructure, if such innovation is to succeed at the system level. They point, as an example, to the failure of a “remarkable” system-wide “Yutori” integrated studies intervention in Japan (Howes, Kaneva, Swanson, & Williams, 2013, p. 10) due to lack of system-wide investment.

3.4.1 Findings from Australian Case Studies

In this section, findings from research into two major Australian STEM teacher development initiatives will be used to illustrate some of the challenges described above for interdisciplinary mathematics, regarding teacher motivations, and student outcomes. The STEM Teacher Enrichment Academy, run by Sydney University, and the ‘Successful Students-STEM’ program, run by Deakin University, each involved teachers of mathematics, science, and technology attending a series of workshops to innovate, with mentoring support, interdisciplinary curricula in their schools. The analysis of these programs, involving field notes, document analysis, and teacher, school leader and student interviews, provided insights into a number of dimensions of interdisciplinary curriculum innovation (Tytler, Williams, Hobbs, & Anderson, 2019).

Models of interdisciplinary curriculum: Variation in approach reflected experience across a wider range of initiatives in Australia and internationally and could be grouped into the following broad models:

- An inter-disciplinary project (sometimes a theme, such as ‘space exploration’, sometimes a design task, such as a sustainable house) with teachers from different subjects planning and teaching together; this was a common model, with mathematics being devised and explored in that class but with some team teaching. There was variation in the extent to which the activity was situated mainly within one subject or equally shared. Often students were assigned different mathematics tasks within the project, depending on their capabilities.
- Cross disciplinary activities within a single subject. Mathematics teachers in one school incorporated science and design work aimed to make mathematics more relevant for students. One activity involved the design of a wheelchair ramp, involving experimenting with the effects of slope, and grappling with appropriate measurement, geometrical and basic trigonometric concepts. Teachers argued an advantage for students in creating and working with their own, real data, and noted the flow on effects for staff in developing more engaging pedagogies and for students in linking mathematics with wider purposes, including social purposes. These are consistent with Williams and colleagues’ findings from a case study of mathematics applied to nutrition, in Williams et al. (2016, p. 27).
- Special STEM project activities; such as robotics days, competitions/challenges, or visits to local STEM facilities or industries.
- A separate integrated STEM unit specifically designed to be inter-disciplinary, with teachers from different subjects contributing.

- In some schools, the focus on STEM involved the explicit planning of digital technology tasks, and progression of skills, across the curriculum.

The process of change: As teachers grew in their collaborative planning and practice, a number of features of the change process were evident, including: (1) growing experience of mathematics teachers in devising tasks and approaches that maintained the integrity of mathematics learning; (2) growing confidence with group-based, student-centred pedagogies, including exploratory tasks and open-ended questioning; (3) professional learning through interactions across the network of schools; and (4) increasing collaboration in planning and implementing projects: in some schools the achievement of a shared purpose was difficult, requiring strategic and sensitive planning processes and leadership support.

Teacher perceptions and student outcomes: A major feature of the motivation for teachers and schools was the perception that 'things had to change' to increase student engagement with deeper learning. For teachers of mathematics, the process of learning to devise approaches to the mathematics involved in the task was not straightforward, but there were indications that they became more confident about this over time. The projects varied in the extent to which the mathematics was central to the task and arose naturally from it, with some tasks involving mathematics, which was somewhat arbitrary and not challenging. However, student interviews indicated students were positive about the fact the mathematics they learnt was for a purpose, and there was evidence from student and teacher interviews of improved attitudes to STEM and potential STEM careers. There were examples, from student notebooks, of significant mathematics learning, consistent with teacher perceptions.

The implications for interdisciplinary mathematics curriculum practice, from analysis of these programs, included (Tytler et al., 2019):

- Within the variety of approaches, the core feature of mathematics in the most compelling cases was the application of the mathematics to 'authentic' projects in ways that were meaningful to students, and involved developing new mathematics, or applying known mathematics in new ways.
- There was no suggestion in any case that mathematics should evolve into an interdisciplinary, as distinct from a disciplinary, practice. Rather, what was involved was the re-alignment of mathematical thinking and working to real-life, complex, problem-oriented contexts.
- For productive mathematics learning in these interdisciplinary settings, tasks should engage students' interest, involve problem solving, involve students in using mathematics in unfamiliar and creative ways, and lead to fresh insights into the problem being pursued.
- Teachers of mathematics found it challenging to develop productive learning opportunities from STEM tasks. This involves a different perspective and skill set and a more responsive view of mathematics learning and knowing.
- There was evidence that students were generally more enthusiastic about mathematics through these interdisciplinary tasks. From students' viewpoint, the

development of mathematics that was immediately applicable and helpful in problems they felt invested in provided significant motivation.
- In all cases, the development and sustaining of these curriculum innovations depended on high-level support from principals and discipline leaders.

3.4.2 Learning Progression Through Interdisciplinary Mathematics

Productive interdisciplinary mathematics curricula involve the authentic generation and application of mathematical knowledge relevant to a real-life project or task. While there is evidence that students find these interdisciplinary settings motivating, and that they see mathematics as more meaningful through its applied purposes, as yet no clear picture has emerged as to the ways in which such work can contribute more fundamentally to progression in mathematical ideas. Generally, interdisciplinary tasks are advocated as a minor part of a mathematics curriculum.

However, there are some models of interdisciplinary curriculum practice that aim to contribute to long-term progression in student learning of foundational mathematical concepts. Richard Lehrer's and Leona Schauble's research, based in the theoretical perspective of model-building and model-based reasoning as a core disciplinary epistemic practice, seeks to ground mathematical learning in progressive experiences of representational invention and refinement. With regard to statistical reasoning for instance, Lehrer and English (2018) explain:

> we take a genetic perspective toward the development of knowledge, attempting to locate productive seeds of understandings of variability that can be cultivated during instruction in ways that expand students' grasp of different aspects and sources of variability (p. 229).

Lehrer and Schauble (Lehrer, 2009; Lehrer & Schauble, 2012) have introduced mathematical modelling in students' investigations of growth and ecosystem function and organization, focusing on measurement. Students explored necessary properties of units and unit iteration that anchor their interpretation of a measure as a ratio: a measured length of 4 units is 4 times as long as a unit length (e.g. Barrett & Clements, 2003). These understandings of the nature of unit and of measurement scale served as resources when students next attempted to measure qualities of natural systems, such as the rate of growth of organisms, such as plants and insects (Lehrer, Schauble, Carpenter, & Penner, 2000). Thus, students' experiences of measure extend beyond the simple 'application' of mathematical principles, and involve invention, evaluation, and refinement of mathematical representational systems, as they re-describe, for instance, plant growth across pictorial, tabular, and graphical modes. Moreover, measures of natural systems are variable, and thus introduce the need for a 'logic of approximation' that stands in contrast to curriculum traditions focusing on mathematical necessity. Discussions of growth variability and approximation in this grade 3 class showed that, under effective guidance, primary students are capable of this deeper kind of reasoning.

These innovative mathematical approaches unlock significant aspects of ecological and natural systems, such as interaction and growth as the determinants of system change, and the science questions that arise tend to lead, in turn, to further mathematical exploration (Lehrer & Schauble, 2012). Currently, we are conducting cross-national interdisciplinary research to explore the extension of this approach to a range of primary school topics (Tytler et al., 2018–2020). The approach is, in principle, possible for secondary schools, although the less flexible timetabling and more scripted curricula could prove challenging.

3.5 Conclusion

The global focus on STEM Education reflects a concern of nation states to build strong economies and enhance societal well-being, coupled with an assumption that the building of a STEM-skilled populace is an important key to this. Perceptions of diminishing engagement of contemporary youth with STEM subjects, and predictions of work futures that will increasingly emphasize STEM-related transportable skills, such as critical thinking, creative problem solving, design thinking, and collaborative team work, as well as STEM disciplinary knowledge in forms that are applicable in authentic settings, has led to calls for a changing emphasis in school STEM curricula. These calls amount to an argument that prevailing content and pedagogies in school mathematics and science are failing to engage students in the sorts of knowledge and skills that will best prepare them for the future. The STEM phenomenon thus represents a challenge to 'business as usual' in school mathematics and science. This applies to all levels of schooling, since decisions to engage or not with STEM futures can be determined at an early age.

Increasingly, STEM rhetoric has been aligned with advocacy of interdisciplinary approaches to mathematics and science learning, built around authentic problem solving and cross-subject interactions. In a number of countries, STEAM, with the A representing creative art and design, has been pursued as a way of enhancing creativity in STEM school practices.

For mathematics, STEM advocacy has renewed a long-standing interest in interdisciplinary approaches. This review has identified a number of possibilities, and a number of challenges for interdisciplinary mathematics. First, there is a dearth of research that would clearly indicate to us the best approaches, and what the outcomes might be. There is wide variability in the nature of integration in the initiatives that have been studied, and variation in the research methods used and outcomes focused on. There is a generally persistent finding that interdisciplinary mathematics curricula lead to improvement in attitudes of students, and to teachers expanding their pedagogical range, but the research is mixed on the effect on student conceptual outcomes. It has been argued, however, that an improvement in student attitudinal responses to mathematics, even if there are no demonstrable short-term gains in learning outcomes, could in the end be a valuable outcome in terms of longer-term learning gains.

Part of the problem with preparing for and supporting system-wide curriculum reform towards interdisciplinary mathematics is that the gains most associated with these approaches—attitudes, problem solving, and metadisciplinary knowledge and skills—are not those traditionally valued and measured. It is also clear that there are a range of blocking factors for interdisciplinary practice in secondary schools, including timetables, organizational structures, teacher training and habits of thinking, and assessment regimes. In order to effect sustainable changes towards interdisciplinary mathematics in STEM, significant commitment is needed at the school and system levels to overcome these barriers, including the development of assessment regimes reflecting STEM skills, such as critical mathematical thinking and creative problem solving.

In terms of disciplinary epistemic integrity, there is evidence that many versions of interdisciplinary STEM tasks fall short of developing significant mathematical thinking and working. Mathematics teachers need to learn new skills, perhaps involving new perspectives on the nature of foundational mathematics concepts, in designing and supporting such mathematical practices in interdisciplinary settings. Paradoxically, it may be that the nature of mathematical disciplinary thinking could be best understood through its development in exploratory real world or interdisciplinary contexts (Lehrer et al., 2000; Williams et al., 2016, p. 16), rather than through the structured within-mathematics practice that currently prevails.

Interdisciplinary approaches are particularly problematic for mathematics partly because of its epistemic character and also the structured and sequential nature of the traditional curriculum. Because of this, advocacy of interdisciplinary mathematics tends to be restricted to short term STEM projects, with the mathematics core pursued without reference to other subjects. However, the work of Lehrer and others opens up possibilities of thinking of ways to pursue a wider range of mathematical topics in a structured way, but within interdisciplinary sequences. It seems clear, however, that this curriculum work cannot easily be done by classroom teachers working within the constraints of traditional schooling structures. There needs to be a serious commitment by systems, supported by significant research and development, if we are to bring the learning possibilities of interdisciplinarity mathematics to fruition.

What Is Needed for this to Occur Is

- A system wide commitment to a mathematics curriculum that meaningfully contributes to developing the STEM knowledge, skills, and attitudes that will prepare youth for the future.
- A program of research and development focused on:
  - Investigating what mathematical learning outcomes should be the focus of a curriculum responding to STEM perspectives
  - Investigating what models of interdisciplinarity, in what topics, lead to engagement of students with these learning outcomes
  - Developing programs of assessment that support such curriculum innovation
  - Developing, in partnership with systems and teachers, structured activity sequences that represent exemplar interdisciplinary curricular practice and

- Developing professional learning approaches that support teachers in interdisciplinary mathematics.

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