STEM and STEAM Education in Australian K–12 Schooling

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To be published in the Oxford Research Encyclopedia of Education, 2021
https://oxfordre.com/
https://doi.org/10.1093/acrefore/9780190264093.013.1684

Summary

STEM (science, technology, engineering, mathematics) education has become a global agenda, with schooling systems around the world in developed and developing countries seeking to incorporate STEM programs into their in-school and out-of-school curricula. While disciplinary integration has been common practice in primary (elementary) schooling for many decades, in the early 21st century the STEM education movement has promoted an increased focus on project- and problem-based learning across disciplines in secondary schools as well. Research suggests, however, that STEM education programs can face barriers in their implementation, often depending on whether they are designed to align with existing curriculum outcomes or whether they are developed as cocurricular programs. Challenges are also presented by the need for professional learning to equip teachers with new skills and knowledge in designing and delivering STEM education. In addition, some researchers and educators have argued for STEAM—integration of the arts in STEM education. For those concerned with school reform, a great strength of STEM and STEAM education approaches lies in the potential for transdisciplinarity. As such, new opportunities and possibilities for framing driving questions and addressing contemporary societal challenges are created. Two particular issues identified as critical are (a) the potential contribution of STEM education to creating a sustainable future, and (b) the importance of STEM education for social justice, in ensuring all children and young people have equitable access to learning opportunities.

Keywords

STEM education, STEAM education, elementary school, primary school, secondary school, cocurricular programs, Australian education

Introduction

In the first two decades of the 21st century, innovation in K–12 school education frequently has been characterized by problem- and project-based learning that transcends disciplinary boundaries and emphasizes real-world learning. Disciplinary integration through STEM and STEAM education has gained popularity in school programs as well as in cocurricular initiatives. While the scope of this article is global, drawing on an international literature including from developing countries, as Australian education researchers we seek to highlight examples from our own country's context. In this article, we take a critical view of STEM and STEAM education in order to reflect on some of the challenges presented by such approaches and the implications for school reform.

The article first provides a critical examination of Australian and broader international research that has a focus on STEM education, to investigate the origins and conceptualization of learning in STEM. Consideration is given to the strengths and limitations of STEM approaches and programs, including STEAM education, illustrated by Australian and international case studies from K–12 schooling. Finally, two issues are discussed that are vital for school reform: STEM for a sustainable future, and STEM for social justice.

Why STEM

The acronym STEM (science, technology, engineering, and mathematics) appeared in the 1990s as a shorthand way of succinctly describing the range of knowledge and skills almost universally regarded as essential to innovation, growth, and global competitiveness in a knowledge economy (Marginson et al., 2013; Sanders, 2009). The term "knowledge economy" came to prominence in the late 20th century (Drucker, 1969; OECD, 1996) as postindustrial nations shifted from manufacturing-based economies to "economies which are directly based on the production, distribution and use of knowledge and information" (OECD, 1996, p. 7). Driven by technology-based products and services and continual innovation, such economies privilege the mathematical, scientific, technological, and problem-solving knowledges on which they rely (Marginson et al., 2013; Sanders, 2009). This shift unpins a near-global consensus that the development and growth of these knowledges are critical to economic and social prosperity (Chesky & Wolfmeyer, 2015; Guile, 2010; Kenway, 2008). The acronym STEM is now ubiquitous in the public domain; however, common usage by the media, industry, and politicians alike conceals the complexity of the nexus between education, employment, and productivity that it has come to represent (National Science Foundation, 2010; Siekmann, 2016).[1]

STEM Education

When talking about STEM education, it is necessary to be mindful of the context in which the term is used. In popular and political usage, STEM education refers simply to education in the disciplines of science, technology, engineering, and mathematics. However, among the academic education research community, it has been interpreted as delivering education in the component disciplines using innovative pedagogies (Timms et al., 2018). The STEM education of the political and public arena is tied firmly to economic goals, whereas the STEM education of the education arena is concerned with transforming learning using student-centered pedagogies. The next subsection is concerned with STEM education as understood at the policy level, and the perspective of the education community follows.

Policy and Strategy Responses to STEM Education

With a series of economic reports in the early 2000s forecasting shortfalls in the supply of the STEM-skilled workforce of several nations (Williams, 2011), the role of schools in developing these essential STEM skills came under increasing scrutiny (Ellison & Allen, 2016; OECD, 1996; Sahlberg, 2010).[2] The need to strengthen science and mathematics education in Organisation for Economic Co-operation and Development (OECD) countries had been recognized since the 1980s (Breiner et al., 2012), as a result of declining secondary student achievement in international benchmark testing together with enrollments in STEM-focused tertiary studies (Ainley et al., 2008; European Review, 2009; OCS, 2012a; OECD, 2006).[3] Reversing these trends became "an almost universal governmental preoccupation" (Marginson et al., 2013, p. 53). Against this backdrop the term "STEM education," although originally used by the National Science Foundation to refer to tertiary enrollments in the fields of science, technology, engineering, and mathematics (DfES, 2004; Kuenzi, 2008; National Academies, 2007), expanded to include K–12 school education as part of the "STEM pipeline," aimed at increasing the flow of suitably qualified and interested students into the STEM tertiary disciplines (Gonzalez & Kuenzi, 2012). STEM education is now understood to encompass the primary, secondary, and tertiary sectors and has become a dominant global policy discourse, linked intrinsically to other popular discourses such as 21st-century skills and innovation (Ellison & Allen, 2016). Education policies and strategies focusing on improving school education outcomes in the STEM disciplines have been implemented worldwide, across developed and developing nations alike, and share the common aim of improving the number of school leavers with competence in STEM skills, particularly science and mathematics. Although such policies and strategies vary across jurisdictions, they fall broadly into the “formal” and “informal” responses (see sections “STEM Education in Schooling in the United Kingdom, United States, and EU,” “STEM Education in Australian Schools,” and “STEM Education in Developing Countries”). For brevity, policy responses to STEM education in the United Kingdom, United States, and European Union (EU) countries are overviewed using these categories, while the Australian response and that of developing countries are described separately.

STEM Education in Schooling in the United Kingdom, United States, and EU

Formal actions impact elements of the overall structure of compulsory schooling, such as mandated curricula and/or assessment regimes, together with actions aimed at increasing the quantity and quality of STEM teachers. In the United Kingdom, rigorous national curricula in mathematics and science were introduced and the structure and level of challenge of external testing were altered (POST, 2013). The introduction of national curricula for mathematics in 2010 and science in 2013 in the United States was a major achievement, overcoming a highly decentralized and politicized education system and establishing a nationwide set of learning standards and definitions of proficiency in mathematics and science for the first time.[5] A further significant development in formal STEM education in the United States has been the rapid growth in publicly funded specialist STEM high schools, promoting inclusive access to an advanced curriculum and expert teachers (Erdogan & Stuessy, 2015). In both the United Kingdom and the United States, substantial effort has been made to upskill existing and out-of-field STEM teachers and attract trainee STEM teachers (House of Commons, 2018; Maltese et al., 2013), and STEM education remains a strategic priority (Campisi, 2019; CoSTEM, 2018; House of Commons, 2018). The majority of EU countries have individually implemented formal STEM education policies and programs, including changes to school curricula aimed at increasing the challenge of selected STEM subjects and emphasizing cross-curricular links (European Schoolnet, 2017).[6] In an overview of STEM education policies in Europe, European Schoolnet (2018) stressed the continued prominence and importance of mathematics education in EU school systems and noted that new methodologies were emerging with the other STEM subjects.

Governments have also directly or indirectly funded or promoted informal programs or activities additional to, but not replacing, formal mandated curricula. These may be developed or approved by education authorities themselves, or they may be developed in-house by a particular school or by organizations external to schools, both for- and not-for-profit, including government agencies.[7] The informal external STEM education sector in the United Kingdom has benefited from increased government funding, with more than 600 organizations providing some form of informal STEM programs to schools (Royal Academy of Engineering, 2016). These programs have generally been directed toward enhancement and enrichment activities, overwhelmingly focusing on the sciences (Royal Academy of Engineering, 2016; Straw et al., 2011; Tomei et al., 2013), although there have been renewed efforts to promote mathematics-focused programs (National Audit Office, 2018). Similarly, U.S. funding led to a rapid rise in the number of informal STEM-related education programs, primarily focused on science (CoSTEM, 2013), including many provided by federal agencies (Kuenzi, 2008). In both countries, duplication and lack of coordination and rigorous evaluation continue to present challenges in identifying and scaling successful STEM education programs and interventions over the long term (National Audit Office, 2018; NRC, 2011, 2013, 2014; PCAST, 2010). In the EU, individual countries have funded and/or established agency partnerships with initiatives in the informal STEM sector (European Schoolnet, 2017). Additionally, two umbrella bodies representing the EU ministries of education are funded with aspects of informal STEM education.[8] The European Schoolnet (2018) overview called for national coordination of the vast number of informal STEM activities and initiatives, in addition to the "maze of STEM resources" online (p. 21).[9]

STEM Education in Australian Schools

Australia has a federalist system, with state and territory governments responsible for the delivery and regulation of school education. Since the early 2000s a series of formal nationwide initiatives aimed at improving the school education system overall have been introduced, and in 2015 national strategies specifically dealing with school STEM education were released.[11] At the federal level, actions encompassed both formal curriculum initiatives and funding third-party program and resource development highly targeted at school mathematics, science, and technology education.[13] States and territories each introduced their own form of STEM school education strategies (NSW Parliamentary Research Service, 2017; Timms et al., 2018). These strategies feature a strong focus on strengthening STEM teachers' skills together with providing a wide range of interventions in schools by way of targeted in-school programs, resources, and professional support (Timms et al., 2018). As with the United Kingdom, United States, and Europe, a great number of private and institutional providers are active in offering informal STEM programs to schools.[14]

STEM Education in Developing Countries

Although there may appear to be parallel STEM policies worldwide, and indeed the intent may be convergent, STEM programs and initiatives play out differently according to local contexts (Marginson et al., 2013). The economic aims of STEM education initiatives in developing countries focus on developing, rather than advancing, the technological and other skills needed to establish a reliable industry base and access existing technologies (Ismail, 2018; Marginson et al., 2013). Increasing consistent and equitable access across all levels of school education to quality mathematics, science, and technology education and improving participation, especially in historically disadvantaged and marginalized populations, is paramount (Marginson et al., 2013). In most cases, government commitment toward the importance of school science and mathematics education is steadfast, and formal initiatives by way of improved curricula and examination regimes, extending the years of compulsory schooling and increasing both the number and qualifications of STEM teachers, are common (Fitzpatrick et al., 2018; Kahn, 2013; Morales, 2019; Republic of Rwanda Ministry of Education, 2020). Limited funding, infrastructure, and political uncertainty have seen both for- and not-for-profit organizations, together with foreign government and industry alliances, providing informal and formal STEM education programs (Executive Secretariat for Integral Development, 2014; Ismail, 2018; Morales, 2019; Siemens Stiftung, 2020). Such programs provide critical expertise, technology, and resources to the local education systems and are often conducted in collaboration with local government agencies (Kärkkäinen & Vincent-Lancrin, 2013). Focusing on a range of issues that impact on both the quality of and access to STEM education, these programs extend from accredited intensive training for public school STEM teachers throughout Latin America, both high school and primary school, through to programs to increase community awareness of, and foster positive attitudes toward, STEM education.[16] These latter initiatives, such as the Kampung STEM Joho (or Joho STEM Village) in Indonesia, are important in countries where historically equal access to education has been limited and gender and other minority stereotypes persist.[17] The chronic underrepresentation of females in the STEM workforce of developing countries has been identified by UNICEF (2020) as a “tremendous waste of talent and human potential” (p. 3). In an effort to address gender bias built into education systems, UNESCO is leading programs across Niger and Uganda to support teacher and principal training in gender-responsive pedagogies across primary and secondary schooling, particularly in the scientific disciplines (UNICEF, 2020).[18]

Responses From the Research Community to STEM Education

In the education arena, STEM education has become associated with some form of integrated teaching and learning experience involving the component disciplines (Blackley & Howell, 2015; Cavalcanti & Mohr-Schroder, 2019; Mohr-Schroeder et al., 2015; Myers & Berkowicz, 2015; NRC, 2014). Integrated STEM education draws its origins and purpose from the rich research foundations of curriculum integration. Originating in the late 19th century and championed by Dewey in the early 20th century, curriculum integration promotes learning that moves away from rigid subject-centered traditions to student-centered pedagogies, advocating active learning in “real-world” contexts (Beane, 1995; Brown & Bousalis, 2018; Dowden, 2011; Pressick-Kilborn & Prescott, 2020). As the name suggests, curriculum integration involves a departure from single-subject curriculum design to involve students in a learning journey where subject boundaries are dissolved and “knowledge is called forth in the context of problems, interests, issues, and concerns at hand” (Beane, 1995, p. 616). Integrated STEM education similarly seeks to blur the boundaries between the component disciplines by positioning learning in authentic contexts, where connecting and negotiating different knowledges mirrors practices in business and industry (Falloon et al., 2020), often through problem- or project-based approaches (Han et al., 2015; Holmlund et al., 2018; Jacques, 2017; Kelley & Knowles, 2016; Sahin, 2019). Variations on the acronym STEM, such as integrated STEAM (where the A is for the arts or agricultural studies), STEMM (where the M is for medicine), or STREAM (where the

R is for reading) extend the knowledge connections beyond the associated economic agenda of STEM education alone. Just as curriculum integration embraces self- and social meaning (Beane, 1995), inherent in integrated STEM education is the development of personal and societal competencies demanded by 21st-century workplaces, such as problem-solving, collaboration, creativity, and innovation (Australian Council for Educational Research, 2016; Han et al., 2015; Holmlund et al., 2018; Ismail, 2018; Johnson, 2013; Mohr-Schroeder et al., 2015; NRC, 2014).

However, despite its longevity, confusion and ambiguity surround the notion of integrated curriculum (Beane, 1995; Czerniak et al., 1999; Dowden, 2011; Drake & Burns, 2004; Meyer et al., 2010; Wang et al., 2011; Weinberg & Sample McMeeking, 2017). This lack of consensus on meaning and conceptual or operational frameworks persists for integrated STEM education, and it is poorly understood by educators themselves (Breiner et al., 2012; English, 2016; Holmlund et al., 2018; Martín-Páez et al., 2019; Nadelson et al., 2012; Weinberg & Sample McMeeking, 2017). The numerous and disparate curriculum frameworks and pedagogical approaches implemented under the guise of integrated STEM education initiatives has hindered rigorous evaluation (Berlin & Lee, 2005; Groves et al., 2017; Guzey et al., 2016; NRC, 2014), and evidence of student academic achievement in the STEM subjects as a result of initiatives is inconclusive (Becker & Park, 2011; Harwell et al., 2015; Munro, 2017; Nathan & Pearson, 2014). The distribution of discipline learning in STEM approaches has emerged as an issue of concern (e.g., English, 2016a, 2016b; Maass et al., 2019), with researchers noting the dominance of science and technology in implemented STEM programs (Clark-Wilson & Ahmed, 2009; English, 2016b; Maass et al., 2019; Pang & Good, 2000; Stohlmann, 2018). This in turn has led to consideration of the epistemic character of STEM (Baldinger et al., 2020; Clarke, 2014; Tytler, 2020), representing as it does the convergence of divergent epistemologies, or an “epistemic stew” (Tytler et al., 2019, p. 53).

Although support for connected learning approaches is expressed in various curriculum documents worldwide (ACARA, 2012; Clough & Olson, 2016; European Schoolnet, 2017), national curriculum documents largely remain structured into single-discipline silos, with students progressing vertically “upwards” through subject silos during the compulsory years of schooling. This vertical structure presents a serious impediment to attempts to integrate horizontally across discipline boundaries in an already crowded curriculum (European Schoolnet, 2018; Nadelson & Seifert, 2017; Rennie et al., 2013; Thibaut et al., 2018; Timms et al., 2018).[19] School environments parallel this framework via timetables, single-subject classrooms, and specialist teachers, particularly in secondary schools (ACARA, 2016; Khalik et al., 2019; Munro, 2017; Rennie et al., 2013; Thibaut et al., 2018; Weinberg & Sample McMeeking, 2017), as well as large-scale accountability assessments (Mockler, 2018; Moss et al., 2019; Nathan & Pearson, 2014; Wallace et al., 2007). Further constraints to implementing integrated STEM education include teacher expertise in both STEM content knowledge and pedagogical approaches, lack of quality, standards-based resources suitable for classroom use, financial and other resource constraints, and, most notably, the time commitment demanded of teachers to plan and deliver an integrated STEM program (Clark-Wilson & Ahmed, 2009; Guzey et al., 2016; Kang, 2019; Nadelson & Seifert, 2013; Stohlmann et al., 2011; Timms et al., 2018; Venville et al., 2002).

Notwithstanding these challenges, widespread interest in integrated STEM education continues. Although replacing subject-specific curricula of STEM subjects with integrated approaches in the compulsory years of schooling remains uncommon and traditional pedagogies persist (Nistor et al., 2018; Rennie et al., 2013), STEM education remains an emerging field (Martín-Páez et al., 2019; NRC, 2014). It has acted as a timely catalyst to reinvigorate consideration of alternative and creative approaches to curriculum design and pedagogies, evolving beyond a simple economic response to encompass the global social and environmental challenges of the 21st century. Examples of such approaches and the social dimension of STEM education are considered in the section "Inclusion of the Arts in STEM."

From the many variations of STEM education, STEAM has emerged as a developing pedagogy rather than simply another acronym. Incorporating the unique perspectives offered by the creative arts, STEAM represents the symbiosis between convergent and divergent thinking (Maeda, 2013), forging the link between creativity and productivity (Liao, 2016). By introducing the creative dimension into the STEM disciplines, STEAM has attracted increasing attention in education as a means of fostering the imaginative thinking and deep enjoyment of learning essential to meet the challenges of the 21st century. Specific focus on the pedagogical innovation of STEAM and implications for teaching and learning is examined in the next section.

Inclusion of the Arts in STEM (STEAM)

Widespread interest in integrated STEM education has also, in some circles, sparked interest in including the arts in the STEM mix, hence the fusion acronym: STEAM. We know that STEM represents integrated science, technology, engineering, and mathematics, and it is important to remember that the arts includes humanities, language, arts, dance, drama, music, visual arts, design, and new media. STEAM can be transformative learning, in that an arts approach may lead to new ways of understanding STEM concepts. STEAM also involves risk. Taylor (2016) considers the basis of transformative learning to be five interconnected ways of knowing: "cultural self-knowing, relational knowing, critical knowing, visionary and ethical knowing, knowing in action" (p. 92). Combined, they transcend perceived discipline boundaries and integrate disparate practices, which comes as no surprise to Root-Bernstein (2019), who argues that innovation is the result of taking “transdisciplinary leaps of imagination” by training scientists, technologists, engineers, and mathematicians “in and with the arts” (p. 11).

Shared views of STEAM as experiential and connected knowledge building (Burnard & Colucci-Gray, 2020; Taylor, 2016; Wagner, 2012) support the regard for such skills as essential to innovation, growth, and global competitiveness in a knowledge economy (Marginson et al., 2013; Sanders, 2009). Twenty-first-century identities are bound up in STEAM, as were those of centuries past; consider Aspasia, Aristotle, Leonardo, Einstein, Buckminster-Fuller. A recent Australian Chief Scientist, while recognizing the needs and attitudes that contribute to positive and flourishing engagement with STEM content at schools and beyond, also suggested that “no clever country would encourage its most STEM-literate people to pursue only traditional research paths” (Finkel, 2016, p. iv). Finkel goes on to say that his own experience would reveal that he found opportunities in unexpected places (Finkel, 2016). For example, the biomimetic “flat to form” STEAM experiences in the unique Lumifold and Binary Bugs activities investigate concepts beyond elementary symmetries, geometry, and binary, extending to constellation mapping, color theory, studies in form and function, and biological systems (Silk & Martin, 2016).[20] This demonstrates how traditional modes of STEM education can be disrupted by integrating content from the arts in ways that embody curiosity, imagination, and challenge in order to relate to real-world concepts.

Explanation of Transdisciplinarity

Transdisciplinarity emerged in response to concerns about the dangers of compartmentalizing areas of knowledge into silos. Bernstein (2015) places Swiss psychologist Jean Piaget at the origin of transdisciplinarity. The word itself appears in a 1970 seminar on interdisciplinarities in universities sponsored by the OECD and the French Ministry of Education, held at the University of Nice. The OECD seminar investigated possibilities of new syntheses of knowledge and the notion of interconnectedness and was led by exposing theories of systems addressing human-centered preferred futures (Bernstein, 2015). This is not unlike the situation we find humanity facing in the early 21st century.

Transdisciplinarity encourages ethical and balanced collaboration between those proffering expertise in different knowledge areas, and collective intent to tackle real problems. Aligned with global shifts to student-centered pedagogies, advocating active learning in "real-world" contexts (Brown & Bousalis, 2018; Dowden, 2011), new terms encountered throughout the Australian curriculum include "innovation," "authenticity," and "real-world learning," as relates to education's cross-curriculum priorities and students' general capabilities (ACARA, 2014). Key features of emerging curricula shift transferable knowledge and skills from subject domain-specific projects to "designing, planning, managing and evaluating across the curriculum" (NESA, 2017, p. 10). It is interesting to note that the relationship between priorities and capabilities is espoused as a way to allow for and encourage integrated and interconnected learning experiences that draw on content across subjects. Georgette Yakman, founder of STEAM Ed, set out to create an integrated learning structure that incorporated all areas of study, fostering student understanding of the importance of the relationship between the fields.[21] Yakman's goal was to destabilize hierarchies, allowing for learners to "hopefully come to respect their need to acquire skills in all areas if they were to become well-rounded citizens" (Yakman, 2008, p. 15).

The complex environment in which we live has redetermined the need for collaboration, communication, and critical thinking across disciplines and fields of knowledge, in order to make sense of the relationship between disciplines and experience (Cranny-Francis, 2017; Finkel, 2016). Understanding discipline differentiation leads to better knowledge of how reciprocal relations, performance, and altruism in education can be achieved in small, close-knit groups as well as distinct pedagogical collegial relationships (UNESCO, 2017). Bernstein

(2015) proposes that "transdisciplinarity is perhaps above all a new way of thinking about, and engaging in, inquiry" (p. 1). Citing Weinberger (2011), Bernstein (2015) considers transdisciplinarity as organizing and thinking about knowledge and inquiry in a "world that has become 'too big to know'" (p. 1), suggesting the word itself has become an important presence in the landscape of integrated education, recognized by some researchers as a "wicked problem" (Tait & Faulkner, 2016).[22]

Inquiry in education contexts may be considered a wicked problem because it spreads across a multitude of educational domains (Bernstein, 2015). Cranny-Francis's (2017) research in cultural studies defines education for the 21st century as an example of a wicked problem, as complexities found through integrating arts and STEM knowledge areas raise significant interest in transdisciplinarity. Such interest arises from the need to lessen the anachronistic view that STEM learning lacks creativity and arts learning lacks scientific rigor (Burnard et al., 2018; Smith, 2018). Clever teachers have been desegregating subject knowledge for a long time. STEAM programs of learning are authentic models of integration where content and experience merge. Transdisciplinarity, as with STEAM, requires flexibility. It spans social and cross-cultural settings. Indigenous Australians have a longstanding tradition of scientific knowledge passed down through song as a memory system (Wade-Leeuwen, 2016). STEAM is adaptable, often collective, always collegial, and never superfluous. It demonstrates intrinsic and extrinsic links between concepts, ideas, and realities and is often filled with wonder. The sciences and the arts were not separable endeavors in the past "but rather as one in their commitment to careful observation, patient experimentation, precise description and informed speculation" (Ingold, 2020, p. 437). Some would say such attributes are sophisticated hallmarks of problem-solving. In STEAM, the interchange between innovation and imagination in so-called problem-solving activities, according to Ingold (2020), is arguably "the way the real sciences – and real scientists – have always worked, by feeling their way from within, guided by genuine wonder, curiosity and care" (p. 437). Genuine wonder and care is enacted in STEAM motivations that cross the globe. Keane and Keane's (2016) development of the creative commons resource NEXT.cc promotes ethical imagination and environmental stewardship.[23] Similarly, The Experience Workshop is a global network of STEAM educators focusing on synergistic learning.[24] These networks aim to foster creativity and innovation across diverse economic and environmental situations, partnering with industry and communities committed to sustainable education futuring.

Creating Together in STEAM Education: Impacts on Teaching and Learning

Neuroscience informs us that the arts and sciences are naturally woven together like creative software in our brains, and that's what compels us to keep inventing (Eagleman, 2018). Regarding opportunities for making connections between STEM and arts concepts, leaders in government, education, and social administration may realize what curious educators have known all along: "the arts are integral and life-giving to the process of learning and the art of living" (Sousa & Pilecki, 2013, p. 154). Yet the diversity of arts integration renders it difficult to locate and pinpoint best practices (Liao, 2016). The creation/production model is suggested as essential for teachers focusing on STEAM. Connecting creative expression and cognitive processes establishes healthy knowledge retention in both domain-specific and domain-general circumstances (Jung et al., 2013). In both arts and STEM learning activities, creative problem-solving and problem-based learning may expand innovative and entrepreneurial thought channels, increasing the range of creative expression and considerably enhancing thinking processes for all involved. Such "tools for thinking," as Root-Bernstein (2019) suggests, "consist essentially of observing, imaging, abstracting, patterning, analogizing, empathizing, dimensional thinking, modelling, playing, transforming and synthesizing" (p. 10). The tools that underpin STEAM's transdisciplinarity are forged through divergent *and* convergent thinking.

If convergence can be described as a meeting or agreement of opinions and actions, occurring at a specific point or degree, it appears that the synthesis forming STEAM from STEM acknowledges the inclusion of the arts as the first step to innovating knowledge building in science, technology, engineering, and mathematics. It would seem that the current prevalence of STEM and the emergence of STEAM, as zeitgeist acronyms in the education arena, implies that transdisciplinary understandings are infiltrating the so-called siloed fields of knowledge operating in many secondary schools. Despite this, the experience of teaching sideways to one's expertise is troublesome for many educators. When establishing the inaugural GMMDC Math Art Competition in 2018, educators from the Nelson Mandela University in Cape Town were concerned that the outcome would not be visually aesthetic and would be too "mathematical."[25] The result was the opposite, aligned with Bishop's view of mathematics as a pan-human phenomenon, deeply embedded in cultural knowledge (Bishop, 1988).

The hype surrounding STEM to STEAM concepts in Australian education, industry, and the general community can be partly attributed to the release of national reports within which alarming statistics related to the uptake of STEM subjects in secondary and tertiary education and recruitment in STEM industries have been widely broadcast.[26] As a result, schools have been prioritizing STEM learning in an attempt to address both tertiary uptake problems and student readiness for inclusion in Industry 4.0.[27] Similarly, the emergence of a range of learning organizations developing and marketing STEM/STEAM programs to schools and communities globally has significantly increased.[28] Given this scenario, it appears that transdisciplinarity in all its forms may be the creative education paradigm desired by many, as an antidote to the current industrialized education system (Robinson, 2010; Sahlberg, 2010; Schleicher, 2018). In a discussion paper on "The Potential Benefits of Divergent Thinking and Metacognitive Skills in STEAM Learning," McAuliffe (2016) proposes that there is significant need for in-depth discussion of the appropriateness of diverse thinking styles when designing and delivering STEAM curricula.

> When designing curricula and teaching it, educators should not mask deeper differences between the disciplines when implementing STEAM activities to improve student learning. Where subject areas are integrated, there is a serious risk that one area will be paid lip service, counted as being covered, but in fact not honoured. (McAuliffe, 2016, p. 8)

McAuliffe (2016) goes on to say that synergetic curriculum content inspires authentic cross-disciplinary fertilization, encouraging curiosity, experimentation, and risk-taking, thus engendering key dispositions of divergent thinking. Ritchhart (2015) proposes we "shatter the paradigm that the best practice of teaching consists largely of the delivery of information" (p. 125), substituting modeling and flexibility, in all its forms, as the proviso for complex, powerful, and nuanced learning. Recommendations from Li (2014), Honey et al. (2014), and Vasquez et al. (2013), suggest that the multifarious concept of spanning discipline boundaries warrants basic understanding of the definition of integration as "working in the context of complex phenomena or situations [using] knowledge and skills from multiple disciplines" (English, 2016b, p. 2). Furthermore, Wagner (2012) asks, "how do we develop young people to become innovators? and seeing this goal as imperative in schools, what do we do? Where do we start as parents, teachers, mentors and employers?" (p. 23). There is nowhere in the literature that says we do this all alone.

Impacts of Transdisciplinarity on Teacher Identity

McAuliffe (2016) proposes that "those who are able to appreciate, integrate and function across the STEAM disciplines are highly prized and … [their] value is increasingly recognised" (p. 2).

For teachers, it may be impossible to put Root-Berstein’s (2019) transdisciplinary “tools for thinking” to use without also experiencing emotions. Learning through STEAM exposes key opportunities for teachers to blend tricky outlaw emotions such as fear, anxiety, and resistance with the activity emotions of joy, elation, wonder, and awe (Silk, 2020). Encouraging teachers to employ STEAM learning as a conduit to knowing and imagining, creating and innovating, may result in a single aesthetic experience (Robinson, 2010) or a series of cumulative experiences that conceivably encounter emotional responses. Hanney (2018) views such liminal teacher states as *doing*, *being*, and *becoming*. Dweck (2008), concurrent with Greene (2018), proposes that a growth mindset would allow a person the *luxury of becoming*, because they are “not yet” (Greene, in Pinar, 1998, p. 1). Indeed, STEAM requires teachers to grow interconnected knowledge through purposeful action by the act of making an effort, and by taking pedagogical risks. Of course, the intention of STEAM is to provide a different perception of learning and knowing (Roth, 1998). Participatory learning in order to augment teacher agency represents Roth’s fundamental concern with effective communities of practice.

Research tracking shifts in teacher identity through engagement with STEAM argues that it *is* possible to set the bar high when designing and implementing STEAM programs in schools. Case studies in Western Sydney (see Figure 1) have shown that while STEAM learning pushes teachers to the edge of their pedagogical comfort zones, the result is personal and professional growth, even for a short time (Silk, 2020).

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If STEAM learning experiences manufacture success and applause, it is a by-product of the good teaching that charts the inner landscape of the collaborating teachers’ lives (Palmer, 1997). Acknowledging collaborative intention and capacity for connectedness, STEAM learning and teaching defends the purpose of innovative pedagogical labors, the by-product of which may shift teacher professional and personal identity, reinforcing the notion that a growth mindset doesn't always need confidence (Dweck, 2008). Drawing on definitive STEAM learning resources such as *From STEM to STEAM: Using Brain-Compatible Strategies to Integrate the Arts* (Sousa & Pilecki, 2013) allows teachers to collectively learn something new and influence others around them. Their emotional contagion demonstrates that "even when you think you're not good at something, you can still plunge into it wholeheartedly and stick to it" (p. 53). This is what students need to witness as they join their teachers in the journey toward the curious and fearsome education readiness called *futuring*.

Shifting STEM Creativity to STEAM "Creativities"

Distinguished Professor of the 3A Institute at the Australian National University Genevieve Bell sees curiosity applied to designing by doing as our fundamental human responsibility in the current digital age and its position in the Anthropocene. "I think we are creating the possibility of a world where what it means to be human will feel very different than it did sixty years ago and I think there are some open questions … about how we navigate that turn" (Bell, 2017, p. 1). In *Why Science and Art Creativities Matter – (Re-)Configuring STEAM in Future-Making Education*, Burnard and Colucci-Gray (2020) have edited a volume of research that unquestionably argues that education is about the future, operating in the face of a turbulent global environmental and political present. In the publication *Why Science and Art Creativities Matter*, the authors focus "on the idea of education as stimulating thinking and practices of future-making, by enabling people and communities to respond resourcefully and creatively to ongoing changes" (Burnard & Colucci-Gray, 2020, p. 1). In education, the creative interchange between teaching, learning, making the world, and participating in a world "in-the-making" determines the interplay between critical thinking and critical connection.

Connected global networks in STEAM continue to provide resources for forward-thinking educators. For example, educators from Hungary, the Netherlands, Italy, Romania, and Finland created *Everyday Creativity: Teacher's Handbook* based on the "Finnish model" of creativity-boosting methods (Szabo et al., 2019). On the ground, we have inspiring educators such as Anita Yu, delivering STEAM programs to middle schools in New York City (Yu, 2015), Fenyvesi et al. (2020) encouraging embodiment of STEM concepts in programs of *Maths in Motion* (MiM), and STEAM immersion programs in Sydney public schools (Silk, 2020), each maintaining the evolution of pedagogical networks with the 22nd-century Cs in mind: care, connection, community, and culture (Santone, 2019; Tomlin, 2018). Sharing stories through embodied mathematics, augmented reality technology, hand-making incorporated with robotics, all show how integrating STEAM domains discourages hierarchical focus on a subject and guides us to think and do through a range of educational modalities. Shifting fields of knowledge through STEAM sketches a plan for active and wide-awake learning experiences that encompass a Deweyan enquiry expressed in visual, verbal, and embodied modes. Drawing on the views of Root-Bernstein and Greene, to transcend disciplinary lines furthers the notion of STEAM education as an "integrated and purposeful intertwining" (Barret et al., 2015, p. 6). It is this intertwining that warrants further dialogue and experimentation to see STEAM framed as the space for "dialectics, debate and openness to a multiplicity of ways of being and doing in the world" (Burnard & Colucci-Gray, 2020, p. 2). UNESCO has identified shifting definable fields of knowledge since the monitoring of global education was implemented early in the 21st century (UNESCO, 2017). Such shifts were a result of increasing specialization and accountability related to overlapping domains. Current evaluations related to achieving quality education categorize accountability as both individual and collective responsibility, action oriented or moral. Indeed, both STEM and STEAM education illustrate how the power of wonder may assist us in navigating education future-making focused on building overlapping cultures of learning that prioritize connection and care.

STEM Education K–12: Two Key Issues for School Reform

The great strength of STEM (and, as argued, STEAM) education approaches lies in the potential for transdisciplinarity, which creates new opportunities and possibilities for framing driving questions and addressing contemporary societal challenges. In this final section of the article we focus specifically on school reform and the promise of STEM education. Two main issues are examined: (a) the potential contribution of STEM education to creating a sustainable future, and (b) the importance of STEM education for social justice, in ensuring all children and young people have equitable access to learning opportunities.

Issue 1: STEM Education for a Sustainable Future

With increasing uncertainty and volatility in our world, the role of STEM education in preparing students to deal with a future characterized by complex challenges arises as a potentially contentious issue (Pitt, 2009; Smith & Watson, 2019). In 2015, the United Nations released the report *Transforming Our World: The 2030 Agenda for Sustainable Development*, which details 17 Sustainable Development Goals (SDGs) toward creating a "plan of action for people, planet and prosperity" (UN, 2015, p. 5) over a span of years. The Agenda focuses on three dimensions of sustainable development—economic, social, and environmental—which has been critiqued by Pitt (2009) and others as potentially fragmented. As highlighted earlier in this article, integrated STEM education has been positioned by proponents as promoting the necessary 21st-century skills (e.g., Ellison & Allen, 2016) and transdisciplinary "STEM mindsets" to address the global social and environmental challenges of this century. There are STEM education projects aligned with the SDGs that focus particularly on social and environmental sustainability.[29] However, critiques of STEM pose challenges to the compatibility of STEM, as a neoliberal project, with the transformative creation of a sustainable future (Smith & Watson, 2019). Smith and Watson (2019) propose that by adopting the lens of “Education for Sustainability,” however, there is potential for STE(A)M to positively contribute to the flourishing of our planet and humanity.[30] The principles of Education for Sustainability outlined by Smith and Watson (2019) are transformation and change; education for all and lifelong learning; systems thinking, envisioning a better future; critical thinking and reflection; participation; and partnerships for change.[31] The challenge, therefore, for school reform appears to lie in how educators locate intersections between STEM and sustainability education in finding a pragmatic and impactful way forward.

There are a number of innovative examples of STE(A)M initiatives that actively engage children and young people in environmental stewardship, including through citizen science projects (Buchanan et al., 2019). “Watershed Education” in the San Francisco Bay Area promotes connections with local waterways and shoreline ecosystems and has a number of programs and events for K–12 students and families, as well as resources for educators.[32] In other U.S. initiatives, Keane and Keane (2016) describe design education approaches that underpin STE(A)M projects that encourage extended student engagement with issues such as renewable energy sources and energy conservation, and the design of green spaces and systems in our cities and schools. In a final example, the Australian “Seeds in Space” schools program aims to engage students in considering the potential impact of plant growth and food supply in space through sending wattle (acacia) seeds to the International Space Station.[33] When the seeds return, they will be planted by students in their schools, with the goal of raising awareness of the importance of acacias in preventing soil erosion as well as promoting students’ interest in plant science.

Issue 2: STEM Education for Social Justice

Equity of access to, and inclusion in, high-quality STEM education programs is essential for K–12 students in promoting social justice. Research studies have focused on school-based and informal (or *free choice*) initiatives designed to enhance participation and engagement of historically underrepresented students, including girls and those from low socioeconomic status (SES) or rural or minority or first nations communities (Bell et al., 2017; Maltese & Tai, 2011; Pinkard et al., 2017; Wilson, 2020). For example, Kennedy and Odell (2014) highlight the incorporation of multicultural and multiperspective viewpoints into STEM programs to engage students, along with connecting STEM educators and students with the broader STEM community and workforce. More recently, Wilson (2020) has highlighted five dimensions or principles of STEM programs particularly designed to engage students from low SES communities: relevance; place and community; experience; creativity and problem-solving; and transfer and action. Wilson (2020) emphasizes that while such principles are particularly important in STEM education in disadvantaged school communities, focusing on contextualized learning experiences that promote active forms of citizenship should benefit all students' learning.

Education programs in informal learning settings, such as museums, public libraries, and local councils, have also contributed to providing equitable access to STEM learning opportunities for K–12 students and their families. Informal opportunities for STEM learning can be particularly valuable in developing countries (Executive Secretariat for Integral Development, 2014; Ismail, 2018; Morales, 2019; Siemens Stiftung, 2020). Such programs can supplement formal schooling by enriching learning of STEM concepts and skills, to promote STEM literacies with opportunities to innovate and invent. For example, Shtivelband et al. (2016) identified a movement in U.S. public libraries toward utilizing and expanding existing resources, such as digital technologies, to offer structured and semistructured out-of-school

STEM programs.[34] Promising practices that enhance equity in STEM learning in public libraries (Shtivelband et al., 2017) included:

- enhancing the visibility of STEM materials in the collection (which ideally should include new technologies and equipment as well as games and books) through displays, blog posts, and activities;
- engaging children's librarians, STEM mentors, and young people in collaborative programming to ensure relevance of STEM initiatives; and
- planning services and events that connect families and communities through intergenerational or multi-age learning opportunities.

These practices are also ones that could be adapted to K–12 school settings, to encourage and inspire wider engagement in STEM learning (Kennedy & Odell, 2014).

Engaging with, and situating learning in relation to, local community settings and holding high expectations are key attributes of successful, socially just STEM initiatives. The "YuMi Deadly Maths" program provides an interesting Australian case study of an initiative that was originally designed for Indigenous students but has subsequently been adapted to low-SES students and mainstream schools.[35] The program focuses not only on providing learning materials for students but also supporting teachers and communities with resources, to promote problem-solving so that students have opportunities to understand their own world mathematically.

Conclusion and Future Directions

STEM education in K–12 schools has gained global prominence since the early 2000s, bringing an emphasis on curriculum integration and innovative pedagogies to promote 21st-century skills and mindsets. Proponents of STEM education argue that transdisciplinary approaches are necessary for addressing current and future social and environmental challenges, and that all students should have opportunities to engage in high-quality STEM programs. The inclusion of the arts—STEAM—adds a focus on creative expression and enables other “tools” for problem-solving. In considering school reform, the STEM education movement promotes engagement in real-world learning and connections with communities. Two issues we have included in this article, STEM education for a sustainable future and STEM education for social justice, also have implications for school reform. The case studies and examples that we have highlighted suggest that there are widespread initiatives that are aligned with K–12 school curricula but also located in informal education and community settings, which creates increased accessibility for children and young people. A human-centered preferred future must necessarily consider the human impact on environmental, psychosocial, and economic systems, and how education primes the interconnected actions and attitudes of players in these systems. Teacher professional development through STEM/STEAM learning experiences can build situations whereby knowledge synthesis and collective intention lead to individual, professional, and systemic kudos. Such learning experiences manufacture success and applause, a by-product of the good teaching that charts the inner landscape of the collaborating teachers’ lives (Palmer, 1997). Acknowledging collaborative intention and capacity for connectedness, STEM/STEAM learning and teaching defends the purpose of innovative pedagogical labors.

Current evaluations related to achieving quality education categorize accountability as both an individual and collective responsibility, action oriented or moral. Indeed, both STEM and STEAM education illustrate how the power of wonder may assist us in navigating education future-making focused on building overlapping cultures of learning that prioritize connection and care. As STEM/STEAM education programs continue to develop and grow globally, we contend that *connection* and *care* are two principles that should guide new initiatives, to ensure positive contributions to sustainable social, economic, and environmental development. This is what students need to witness as they join their teachers in the journey toward the curious and fearsome education readiness called *futuring*.

Acknowledgments

We would like to acknowledge the many colleagues and collaborators in our research endeavors, particularly students and teachers who have participated in our respective projects, and academic staff at the University of Technology Sydney, Australia.

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Figure 1. Photographic montage showing teachers (and students) participating in STEAM activities related to making with mathematics as part of doctoral research supervised by the University of Technology Sydney (Silk, 2020). Each image included in the montage is reprinted with permission from research participants as per approval from UTS Human Research Ethics Committee (HREC), reference number ETH17-1213.

Notes

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[1] For example, “STEM skills” (Avery, 2015), “STEM indicators” (Reading et al., 2015), “STEM teachers” (Latifi, 2018), or simply “STEM” (Singhal, 2018).

[2] For example, the 2002 *SET for Success* (Roberts, 2002) report in the United Kingdom, the 2007 *Rising Above the Gathering Storm* (NRC, 2007) report in the United States, and the *Health of Australian Science* (OCS, 2012a) and *Mathematics, Engineering and Science in the National Interest* (OCS, 2012b) reports in Australia.

[3] This benchmark testing comprises Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA). TIMSS is an international comparative study of student achievement directed by the International Association for the Evaluation

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of Educational Achievement of students in years 4 and 8 in mathematics and science conducted every four years in participating education systems and countries. PISA is an international comparative study of student achievement directed by the Organisation for Economic Co-operation and Development (OECD) and assesses science, reading, and mathematics literacy of 15-year-old students every three years in OECD and partner countries.

[5] *Common Core Standards for Mathematics[http://www.corestandards.org/Math/]*; *Next Generation Science Standards[https://www.nextgenscience.org/]*.

[6] For example, changes to the French mathematics curriculum in 2010 (Oliveira & Roberts, 2013).

[7] For example, the iSTEM syllabus approved by the NSW Education Standards Authority (NESA) as an optional subject for years 9 and 10 of secondary school.

[8] European Schoolnet focuses on evidence-based innovation in teaching and learning, while InGenius specifically focuses on providing best practice STEM education resources and promoting science education.

[9] By 2013 there were estimated to have been between 3,000 and 5,000 STEM initiatives in Europe (Durando, 2013).

[11] The nationwide initiatives included introducing professional standards for teachers, a framework to measure the mathematics, science, and information technology performance of Australian schoolchildren, and a national curriculum. The *National STEM School Education Strategy 2016–2026* (Education Council, 2015) was followed by the *National Innovation and Science Agenda* (Commonwealth Government, 2015) and *Australia's National Science Statement 2017* (Commonwealth Government, 2017).

[13] Formal curriculum initiatives refers to the development of a digital technologies curriculum for schools. Examples of third-party programs include *Let's Count Maths*, *Primary Connections*, and *Science by Doing*; *Digital Technologies Challenges*.

[14] For example, the *STARportal[https://starportal.edu.au/]*, launched in 2017 and hosted by a federal agency, provides a searchable database of more than 650 STEM activities.

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[16] STEM Brasil and siSTEMa Educando in Mexico are high school initiatives of Educando, a Worldfund program, while the Experimento program developed and sponsored by Siemens Stiftung is for primary schools.

[17] *Kampung STEM Joho[https://www.australiaawardsindonesia.org/article/detail/638/279/stem-science-technology-engineering-mathematics-village-joho-kampung-stem-joho]*.

[18] These are instituted under UNESCO's CapEd Programme.

[19] An exception is the Danish KOM curriculum, which emphasizes skills and application focused approach to mathematics, making it easier to integrate with other subjects (Timms et al., 2018).

[20] Lumifold and Binary Bugs are STEAM "making" activities incorporating specific mathematics related to binary, elementary symmetries, iteration, and translation. A glide reflection pattern is provided in pre-scored paper in order for makers to transform two-dimensional flat sheets into three-dimensional shapes. The geometric shapes constructed during the activity demonstrate contrasting physical properties of stability and flexibility. In their final state of construction, the shapes are illuminated with small LEDs to highlight the biomimetic nature of the forms and delight the makers. See *STEAMpop[https://steampop.zone/index.html]*.

[21] *STEAM Ed[https://steamedu.com/about-us/]* was founded in 2006, aiming to provide a framework for "FUNctional literacy for all" using the idea that science and technology are interpreted through engineering and the (social, language, physical, musical, and fine) arts, all based in elements of mathematics. The ST∑@M© pyramid ascends from content-specific and discipline-specific learning, through multidisciplinary, integrative, and lifelong learning.

[22] The term was originally identified by design theorists Horst W. J. Rittel and Melvin M. Webber (1973)<AU: Please add to References>, and more recently popularized through human-centered designer Bruce Mau, within his exploration of complexity, *Incomplete Manifesto for Growth* (Mau, 1998).

[23] *NEXT.cc[https://www.next.cc/]* is an eco web that develops ethical imagination and environmental stewardship. NEXT.cc introduces what design is, what design does, and why design is important. It offers activities across nine scales—nano, pattern, object, space, architecture, neighborhood, urban,

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region, and world. NEXT.cc’s journeys introduce activities online, in the classroom, in the community, and globally. NEXT.cc journeys and activities are supported with links to museums, institutions, and contemporary practices<AU: If this text is a quote, please enclose in double quotes>.

[24] *Experience Workshop[http://www.elmenymuhely.hu/]* began in 2008 as a collaborative effort of mathematicians, artists, toymakers, craftspeople, teachers, parents, and children, and has grown into an open STEAM community of professional educators, researchers, and artists devoted to creative agency in the field of STEAM<AU: If this text is a quote, please enclose in double quotes>.

[25] The Govan Mbeki Mathematics Development Centre within the Nelson Mandela University initiated the 2018 Math Art Competition to engage with students from underresourced and poorer communities across Eastern Cape Secondary Schools in South Africa. The competition is now a national event open to learners from grades 8–12. Students can use any visual medium, including photography, drawing, painting, collage, or mixed media, to represent a mathematical concept stipulated by the competition organizers from year to year. This very successful initiative asks students to provide an artist statement with each submission, describing the mathematical connection to their art and their own unique perspective justifying their choice. https://science.mandela.ac.za/News-Archive-en/GMMDC-Math-Art-Competition

https://www.rnews.co.za/article/nelson-mandela-university-maths-art-competition-goes-national<AU: Please include articles in References and use in text citation forms here; the links were not working for me, please check that they are valid.>

[26] See note 11.

[27] The fourth industrial revolution, also known as *Industry 4.0[https://www.industry.gov.au/funding-and-incentives/industry-40]*, is affecting almost every industry worldwide. It is rapidly transforming how businesses operate. Industry 4.0 uses transformative technologies to connect the physical world with the digital world.

[28] For example, *EduSTEM[https://www.edustem.com.au/]*—Project Based Learning (PBL) activities aimed at increasing engagement and improving understanding using practical, hands-on approaches that are proposed to be easily incorporated into any subject; and STEAMedu—first research and most

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globally recognized STEAM educational institution enabling science and technology interpretations through engineering and the arts, “all based in mathematical elements.”™

[29] For example, **Science on Stage Europe*[https://www.science-on-stage.eu/page/display/3/104/0/sustainability-in-stem-education]*.

[30] “Earth as an interconnected, complex and materially finite system … explicitly critical, activist and socially transformative rather than socially reproductive” (Smith & Watson, 2019, p. 2).

[31] With reference to the Australian Government’s National Action Plan for Education for Sustainability, *Living Sustainably* (Australian Government DEWHA, 2009).

[32] *Watershed Education[http://thewatershedproject.org/our-programs/watershed-education/]*.

[33] *What’ll Happen to the Wattle?[https://onegiantleapfoundation.com.au/whatll-happen-to-the-wattle/]*. See also the related *NASA initiative[https://www.nasa.gov/feature/growing-interest-students-plant-seeds-to-help-nasa-farm-in-space]*.

[34] See also *STAR_net[http://www.starnetlibraries.org]*.

[35] Queensland University of Technology, *YuMi Deadly Maths[https://research.qut.edu.au/ydc/about/yumi-deadly-maths/]*.