Chapter 11
Final Commentary: "Education in the 21st Century: STEM, Creativity and Critical Thinking"

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Abstract This chapter offers a reflective commentary on the contribution of the book as a whole, taking up the idea supported by the book's authors that STEM education can, and needs to be, much more than an educational reform agenda to supply a future global workforce. Based on the work of the authors, a set of key themes is identified and discussed that can progress the development of STEM education, nationally and internationally. These themes include: embracing contemporary views of education, developing skills and capabilities such as critical thinking and creativity, engaging with societal issues of social justice and equity (including the role of empathy), and better understanding the nature of teacher expertise and its development.

Keywords STEM education · Teacher professional knowledge · Policy · Collaboration · GERM theory

11.1 Introduction

In this final chapter, I offer a reflective commentary on the contribution of the book as a whole, taking up the idea supported by the book's authors that STEM education can, and needs to be, much more than an educational reform agenda to supply a future global workforce. It was intentional in our conceptualisation of this book and in the workshop discussions that the chapter authors would offer a perspective of STEM education that includes a much broader and more inclusive vision of schooling and education than STEM for economic and employment purposes. This vision embraces the view that STEM education can, and should, contribute to a better global society and its citizenry, through preparing students who can effectively respond to multi-faceted economic, social and environmental challenges, such as

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those foregrounded by COVID-19 and climate change (Corrigan, 2020). In this way, we distinguish between notions of STEM as a workforce development initiative, and STEM education, as distinct and necessarily different terms.

Emerging from the book's chapters is a set of key themes that we hope will help to progress the development of STEM education, nationally and internationally. These themes include: embracing contemporary views of education, developing skills and capabilities such as critical thinking and creativity, engaging with societal issues of social justice and equity (including the role of empathy), and better understanding the nature of teacher expertise and its development. While individual chapters may address one or more of these themes, at the heart of this book, it is clear that none of these entities exist in isolation. They are deeply entwined. Understanding how they are entwined, and in what contexts, and how they are central to STEM education, is a consistent focus throughout the chapters.

11.2 STEM: A Phenomenon of Global Interest

In Chap. 1, we outlined how the notion of STEM has rapidly captured international interest and emerged as an educational phenomenon. The global focus on STEM has been driven primarily by external forces to serve economic and vocational goals, funded by governments and typically promoted by politicians and industry (Blackley & Howell, 2015). As a consequence of the involvement of different interest groups and their agendas for STEM, different meanings of STEM have emerged and been pursued, including STEM as a set of career fields, a collective noun for the separate disciplines of the sciences, mathematics, engineering and technology, and as an integrated approach to curriculum (often referred to as integrated STEM). These different meanings have subsequently led to varied STEM narratives that have, in turn, influenced the kinds of strategies and programmes that have been pursued in schools and other educational contexts.

For example, in Australia (my home country), concerns about a limited supply of future STEM workers has led to STEM becoming imposed on schools as an employment problem to solve. Added to this, falling interest and participation rates in senior science and mathematics and low levels of student achievement against international benchmarks, have led to a discourse of "STEM in crisis" (Marginson et al., 2013, p. 55). Proposed solutions typically include adding more science and mathematics into school programmes, a focus on student mastery of disciplinary content, and recruiting more teachers with strong disciplinary backgrounds in science and mathematics. However, more recently, the STEM crisis has been labeled as "a myth" (Ritchie, 2019) that was created to drive policy to promote STEM education that would address future workforce demands and increase achievement in cross-country comparisons resulting from high-stakes international testing (e.g., TIMSS and PISA), results acting as a proxy for quality education.

STEM as a global education policy is now further explored.

11.3 STEM: A Kind of "GERM"?

In Chap. 1, we referred to the dramatic and devastating effects of the novel corona virus (COVID-19) on humanity. As a rapidly spreading and hard to control infection, COVID-19 has vastly changed our ways of living in a very short period of time. An important factor contributing to the rapid spread of COVID-19 is globalisation: the increased, large-scale mobility of people and goods around the world. Similarly, globalisation has been an important factor influencing the spread of large-scale educational reforms, such as STEM. In education, these reforms are typically driven by a focus on improved educational performance through factors such as competition and standardisation. Sahlberg (2011) coined the metaphor-acronym 'GERM' — Global Education Reform Movement — to describe the pervasive spread of reforms through education policy that "infects education systems" worldwide. STEM education is an obvious example of a GERM. Promoted as an educational imperative that can improve national competitiveness, drive economic expansion and transform society, the STEM education agenda is highly influenced by forces from outside of education (e.g., government, industry) with significant impacts on schools and teachers.

Sahlberg (2011) described six features of GERMs that have aimed to improve education but that have problematic side effects:

1. Standardisation of, and in, education: This shifts the nature of teaching from an open-ended, non-linear process of mutual inquiry and exploration to a linear process with causal outcomes. Standardisation may also restrict creativity and innovation in teaching and learning.
2. Focus on literacy and numeracy: This sets up silos in these areas and reduces focus on other subjects.
3. Teaching for pre-determined results: This minimises risk-taking in teaching and learning and, therefore, reduces opportunities for creativity.
4. Market-oriented reform ideas: These distance teachers from the moral purpose of their profession.
5. Test-based accountability: This increases instances of teaching to the test.
6. Control: This diminishes autonomy of teachers and the degrees of freedom of schools. This can lead to teaching that aims to showcase good practices rather than genuinely helping students to learn.

Several of these GERM features are evident in efforts to drive STEM education. For example, focusing measures of success in terms of student achievement in individual STEM subjects, assessing STEM features such as critical and creative thinking as specific measurable entities, focusing on the products of STEM rather than its processes (e.g., in terms of students producing products for market), and collapsing the STEM disciplines into one entity, thus distorting views of their distinctiveness (e.g., the notion of failure as the same in each of the STEM disciplines, c.f. Mansfield & Gunstone, Chap. 9). If we are to avoid succumbing to the side effects associated with a GERM agenda, framing what STEM can, and should, look like in education requires engaging with fundamental questions about the purposes of contemporary schooling and what makes a *good education*, including the role of teachers in educational reform. Rather than essentialising STEM as a high-performance competition or training for industry, a “STEM education” needs to take into account broader society aspirations:

> Framing the primary purpose of schooling and STEM course work in terms of job preparation, economic growth and national security is problematic… [These] are, at best, only very loosely tied to the general state of schooling, and the need for a technical workforce does not provide a compelling impetus for most children to value STEM learning… a K-12 system focused on job preparation cannot keep up with the ever-shifting job market and would ill-prepare such individuals when such changes inevitably occur. … A STEM education, as opposed to a mere training, would draw from and dignify the humanities in a common effort to prepare individuals for engaged citizenship which includes judiciously assessing the pros and cons of STEM for improving personal and societal welfare. (Zeidler et al., 2016, p. 466)

In the sciences, there is a long history of the failure of major curriculum reform initiatives aimed at increasing the post-school scientific workforce. In fact, the best school science preparation for potential scientists in contemporary times has shown to be the same broad and socially contextualised form of school science education that has been argued across the last five decades as best for those *not* planning a scientific career (Smith & Gunstone, 2009).

The contributors to this book offer a very different vision of the purposes and processes of STEM education. This vision transcends a GERM like interpretation, and may even offer ways of vaccinating teachers and schools against a view of STEM as GERM. Through their individual chapters, the authors collectively highlight an important theme: that STEM education in formal and informal contexts has potential to offer an approach to working with, and preparing, young people to actively, thoughtfully and productively participate in all aspects of society through engaging their interests in, and commitment to, STEM. This view of STEM as enabling young people’s informed, civic participation in Science, Technology, Engineering and Mathematics has important implications for teachers, students and schooling.

11.4 What the Chapters Show Us About STEM Education

The chapters of this book show us that STEM education can (and should) be defined in different ways according to need and context; that STEM education goes beyond the teaching of the individual disciplines within their silos; and that STEM education involves learning and using different ways of thinking and knowing, collaborating across and within different groups (within and outside of schools), and learning about and taking risks. Each of these features of STEM education is elaborated below, along with illustrative examples from each of the chapters.

11.4.1 STEM Education Should Be Defined According to Need and Context

One of the challenges of STEM education is in the label itself. What does 'STEM' actually mean in the context of education? Earlier I pointed out that STEM is broadly associated with the individual disciplines of its acronym, or as a set of career fields. In schools, STEM education has taken on a variety of meanings, including the teaching and learning of one or more of the four individual disciplines, or in an integrated way (in combinations of two, three or four of the disciplines); and/or a focus on particular skills and capabilities, such as critical thinking and creativity, or metacognitive skills, such as learning to monitor one's own learning. This multiplicity of meanings and applications of STEM in education is both problematic and useful. On the one hand it allows stakeholders, within their particular and unique contexts, to define STEM in ways that best suit their needs; on the other, it may lead to STEM education being interpreted as 'anything goes'. For example, some interpretations of STEM emphasise the importance of including lots of 'hands-on activities', which research has demonstrated may actually reduce opportunities for students' meaningful learning when these are the primary or sole focus (see, for example, Berry et al., 2001).

One issue taken up by contributors to this book is how the meaning of STEM education has been interpreted through the curriculum. The development of STEM education curriculum should plot a path to be taken, rather than a detailed syllabus specifying exactly what teachers need to do. For example, Buntting and Jones (Chap. 5) point out that in the New Zealand context, the national curriculum provides a broad set of learning aims and attributes to be developed, such as innovation, inquiry and curiosity; and key competencies, including creative and critical thinking and relating to others. Within this national curriculum, schools and teachers have the autonomy to develop locally relevant STEM curriculum and are encouraged to make natural connections across learning areas, values and key competencies.

Rennie (Chap. 7) expands on the important role of curriculum, recalling Ralph Tyler's (1949) notion that curriculum should help in realising the goals of education through asking, *What are the purposes of learning? How can learning experiences be organised and evaluated to realise these purposes?* Rennie distinguishes between two dimensions of curriculum: the balance between disciplinary and integrated knowledge (where 'knowledge' is used holistically to include accompanying skills and capabilities), and the balance between local and global types of knowledge (Rennie et al., 2012). Any curriculum should offer balance and connection across both of these dimensions. Elsewhere, Rennie (1990) has emphasised the need for students to "experience a meaning and a context for what they have the opportunity to learn." Otherwise, "they are unlikely to learn it" (p. 191). Importantly, both Chap. 5 and Chap. 7 highlight the more open notion of curriculum as a framework to be developed in context, rather than positioning curriculum as a heavily specified pathway in a syllabus.

Critical to realising a relevant and meaningful STEM curriculum is the opportunity for building a shared understanding of its purposes. This point underpins Chap. 2 by Kelly and Ellerton and Chap. 3 by Vincent-Lancrin. Kelly and Ellerton point out that the combination of the concepts of creativity and critical thinking provides a very potent avenue for integrated STEM educational practices. Establishing a shared understanding of each of these concepts and their mutual dependence is developed throughout the chapter: critical thinking permeates every aspect of creative practice, while creative practice catalyses the growth and complexity of critical thinking.

In Chap. 3, Vincent-Lancrin reports on an OECD project that seeks to foster and assess creativity and critical thinking through identifying some of the elements that could lead to a common understanding of these ideas, and how teaching and learning strategies aligned to the development of creativity and critical thinking can be applied in both domain-specific (science) and domain-general ways. Vincent-Lancrin describes two domain-general conceptual rubrics for assessing creativity and critical thinking, including a "comprehensive" rubric and "class-friendly" rubric. An important purpose for creating these rubrics is to assist teachers to apply their understandings of creativity and critical thinking *to their own teaching and learning contexts*. To further support teachers, Vincent-Lancrin outlines a set of "design criteria," including motivation, cognitive activation, and self-regulation, as well as opportunities for formative assessment that teachers can consider when designing science learning experiences that support their students to develop students' creativity and critical thinking capabilities. While the design criteria are important, successful teaching of creativity and critical thinking also relies on teachers' attitudes and abilities to create suitable learning environments where risks, failure and mistakes are a naturally accepted part of the learning process (see Chap. 5 by Buntting and Jones; issues of risk and failure in science and mathematics learning is taken up in detail in Chap. 9 by Mansfield and Gunstone).

The influence of context on how teachers define and put into practice creativity and critical thinking is further elaborated in Chap. 6, by Corrigan, Pannizon and Smith. In their study of developing creativity and critical thinking across early childhood, primary and secondary school networks, they found that context shaped the pedagogical approaches teachers utilised to develop these capabilities in their students. In other words, the age of the children made a difference. For example, in early childhood settings, when asked to explicitly develop creativity and critical thinking, teachers tended to focus on open-ended approaches that were both planned and incidental in nature. In primary schools, problem-based learning and thinking routines featured prominently, while in secondary schools, teachers sought to develop a shared understanding of creativity and critical thinking and considered how they might be applied in specific disciplines. The findings from Corrigan, Pannizon and Smith's study highlight the need for teachers to translate the concepts of creativity, critical thinking and the integrated nature of STEM into their practical realities. Another key insight is that, as the teachers reflected on their current ideas and practices and sought to incorporate opportunities to further develop students' thinking, either by drawing on existing approaches or developing new ones, they began to work more collaboratively, clarifying their individual and collective understanding of these ideas and how to implement them.

Clearly, across the different interpretations of STEM education described by the authors of this book, there is an emphasis on the need for teachers to be actively involved in decisions about what matters and why in their own contexts. This active decision making of teachers needs to include how to incorporate the learning of different skills and capabilities within a STEM education curriculum. Of course, having some support and guidance is helpful for teachers as they develop and implement curriculum change, but that is not the same as a prescriptive, one-size-fits-all template. In this respect, teachers and schools need to be trusted to make decisions about what is best for their students.

The different examples offered by the authors of this book also highlight the important notion of STEM as “a collection of evolving ideas rather than a specific approach or practice” (Siegel & Giamellaro, 2019, p. 757). STEM education cannot rely on any specific approach or practice, as each context in which it is enacted will be unique.

11.4.2 STEM Education Goes Beyond the Individual Teaching of Disciplines to Become “Ways of Thinking and Working”

The contributors to this book propose a view of STEM education that goes beyond the boundaries of its individual disciplines to embrace a more local, context-driven, interdisciplinary approach that draws on and connects particular ways of thinking and working. However, as Tan points out (Chap. 10), the traditions of curriculum and schooling may make such a goal difficult to realise. For example, long-standing and deeply-engrained views of what comprises each of the individual STEM disciplines, including what students need to learn and in what order, particularly in science and mathematics, have a powerful effect on shaping the structure of curriculum and schooling, and have shown remarkable resistance to efforts for change.

Going beyond the traditional structures and ways of working of individual STEM subjects also requires knowing how to meaningfully incorporate opportunities for developing creativity and critical thinking into STEM learning. As Kelly and Ellerton (Chap. 2) note, “It is important to view creativity and critical thinking in concert to fully understand their interrelatedness and the educational ecosystem they enable to maximise educational potentials in STEM education”. Kelly and Ellerton also recognise the tensions associated with existing disciplinary traditions and raise the question of “how to operationalise creativity in educational practice against a backdrop of such traditional educational discourses”.

In order to take an integrated approach to STEM education, Buntting and Jones (Chap. 5) highlight the need for teachers to be able to understand and navigate the different discourses of the STEM disciplines. Through the case study of one teacher, James, their chapter explores the professional knowledge and skills that teachers needed to scaffold students' STEM learning, and the value of focused learning conversations with students to support their creativity and critical thinking. Buntting and Jones also remind us of the complexity of this task for teachers, who need to be able to recognise and navigate the different scientific, mathematical, technological and everyday discourses, and know which discourse to use when and where, if they are to support students' conceptual and skill development throughout a STEM sequence of learning. This could be a key aspect to be addressed in teachers' professional learning and development.

Corrigan, Panizzon and Smith (Chap. 6) similarly advocate the need for teachers and students to understand the different forms of expertise embedded within and across the STEM disciplines. Their study provided opportunities for teachers to investigate differences between the STEM disciplinary areas and build an appreciation of how working *across* the STEM disciplines can open up new possibilities for student learning. Corrigan et al. also identified that while there is a growing emphasis on developing students' ways of thinking, teachers tend to perceive these as 'add-ons' to the curriculum, and they are often applied in a tokenistic rather than integrated manner. Here, rubrics for creative and critical thinking, such as those discussed by Vincent-Lancrin (Chap. 3) may assist teachers to embed these ways of thinking more purposefully within the curriculum.

Seeing what the integration of the STEM disciplines can look like and how this can be operationalised in practice is a focus of Rennie's work (Chap. 7). Her chapter explores how effective integrated curricula with an out-of-school component encourages students to develop their STEM understanding and skills. Three important aspects of this approach are highlighted:

1. using real-world, authentic contexts that can meaningfully bring together disciplinary and interdisciplinary knowledge;
2. working outside of the regular classroom to show students a "bigger picture"; and
3. working on issues that are important to the local community, and/or matters relating to social values and diversity, provides students with opportunities to develop their senses of social and ecojustice.

Through such integrated learning opportunities, associated thinking skills and capabilities can be developed. Drawing on the OECD's dimensions of creativity and critical thinking – inquiring, imagining, doing, and reflecting – can be helpful to illustrate how guiding students to interact with local, place-based, or community issues can enhance their creativity and critical thinking, as well as their communication and collaboration skills.

The three aspects highlighted by Rennie above, are also evident in the chapter by Cowie and Midenhall (Chap. 4), who also show how operationalising the STEM disciplines through integrated approaches can play a role in developing students' sense of social justice. Through the presentation of three vignettes of classroom practice, Cowie and Mildenhall illustrate how approaches that incorporate the development of knowledge, empathy and action, can support students' capacity for critical and creative thinking and the inclination to take constructive action for wider societal ‘good’.

Cheng and Leung (Chap. 8) extend the idea of socio-scientific aspects of STEM education into higher education through their example of an interdisciplinary course that aims to engage students in “a critical scrutiny of their thinking and of the information they come across,” focusing on the specific issue of obesity. Cheng and Leung highlight how working across the STEM disciplines helps students to develop an appreciation for different ways of thinking, for example, technocratic ways of thinking (based on scientific rigour) versus emancipatory thinking (based on ethical and political scrutiny of an issue). Their approach provides an interesting example of what it means to operationalise student learning in more transdisciplinary ways, where the boundaries between different disciplines and ways of thinking are challenged and become intentionally blurred.

Collectively, the book’s examples described above provide a range of possibilities for moving beyond STEM as ‘siloed’. However, it is also important not to lose sight of the value of the individual disciplines themselves and their unique ways of working and thinking. Indeed, the contributors to this book are not suggesting blending the individual disciplines into what Lehrer (2016) calls an “epistemic stew,” but instead, becoming cognisant of what each discipline contributes and how the disciplines can be meaningfully drawn upon and connected in the development of student learning.

11.4.3 STEM Education Involves Collaboration

The chapters of this book illustrate that collaboration is an important component of STEM education, and that collaboration looks different according to the learning purpose(s) and context. For example, collaboration can include teachers within a department or school, across schools or across school sectors (e.g., schools and universities), between students within or across grade levels or schools, and between schools and communities/industry in their local or broader contexts. However, popular interpretations of collaboration are often rather loosely defined as ‘simply’ working in groups. Collaboration needs to be purposefully planned, drawing on different kinds of social and cultural activities, such as learning to work with others, engaging in active discussion and shared decision making, and joint problem solving.

The OECD (2005) identifies collaboration as a multi-faceted key competency for the twenty-first century. It requires:

- the ability to relate well to others, including demonstrating empathy and effective management of one’s own emotions;
- the ability to cooperate in terms of presenting ideas and listening to those of others, understanding the dynamics of debate, being able to follow an agenda, being

able to construct tactical or sustainable alliances, being able to negotiate and make decisions that allow for different shades of opinion; and

- the ability to manage and resolve conflicts where issues are analysed for different interests, such as power, equity, recognition of merit and division of work, the origins of conflict, the reasoning positions of different sides and recognition of different possible solutions, being able to identify areas of agreement and disagreement, to reframe a problem, and prioritise needs and goals including deciding what you are willing to give up and under what circumstances.

Chapter authors provide insights into different kinds of collaboration, why it matters, and what can be learned through collaborating. At the most fundamental level, Kelly and Ellerton (Chap. 2) highlight the social collaborative nature needed for STEM education in terms of the development of students' collaborative and communication capacity. Other chapters provide examples of how collaborative relationships link with particular learning purposes. For example, Rennie (Chap. 7) describes how a school and local industry collaboration supported students' learning about local environmental issues, where the collaboration was developed between different groupings of students, teachers, experts, parents and the general public. These varied types of collaboration helped students to develop multiple project outcomes as well as to negotiate decisions about which solution(s) would be the most appropriate to pursue. Cowie and Mildenhall (Chap. 4) highlight a collaborative relationship between students and a local community group that resulted in students developing a strong sense of community and that their ideas were listened to and mattered, while the members of the community group gained a renewed sense of purpose in helping others. Buntting and Jones (Chap. 5) alludes to the benefits of collaboration between teachers and researchers, as well the more obvious teacher/student and student/student collaborations. Corrigan, Pannizon and Smith (Chap. 6) highlight how collaboration across the early childhood, primary, secondary and tertiary sectors supported teacher and researcher learning about effective pedagogies. Specifically, sharing professional knowledge beyond individual teachers and sites helped to build collective capacity and shared understanding of ideas that not only benefited the teachers, but that also provided a model for how students might work together. In a similar vein, Cheng and Leung (Chap. 8) demonstrate how collaborations between university educators across different faculties can support student learning in a general university course based on a socio-scientific issue.

Overall, the role of collaboration highlights STEM education as a sociocultural activity that is simultaneously "active, contextual, co-constructed, and continually evolving" (Siegel & Giamellaro, 2019, p. 768). However, thinking about STEM in this way also presents challenges for its implementation, where traditional educational structures and processes present barriers in terms of (for example) time tabling, non-alignment of curriculum, and the need to specify and standardise predetermined learning outcomes rather than allowing these to evolve through a project. Seeing STEM education as a sociocultural activity that involves co-construction and that evolves over time according to need, interest and resources, requires system flexibility that the chapter authors show is possible – but that requires commitment and motivation of both teachers and educational leaders.

11.4.4 STEM Education Involves Risk

Biesta (2013) identified that

> …real education always involves a risk…The risk is there because, as W. B. Yeats has put it, education is not about filling a bucket but about lighting a fire….The risk is there because students are not to be seen as objects to be moulded and disciplined, but as subjects of action and responsibility. (p. 1)

If 'real education' involves risk, it is tragic that education systems are typically set up for risk aversion. This is evident through the many control mechanisms built into the schooling system, for example, through a tightly regulated curriculum, and standardised assessment and reporting procedures that keep teachers and schools highly accountable for their performance. Under such conditions, the opportunity for "real education" in Biesta's terms, becomes very difficult. Viewed from a STEM perspective, a significant tension emerges between what is often promoted as central to STEM education, that is, engaging with risk and failure (e.g., through design and prototyping), and the performance-related, risk-averse nature of formal education. Many of the authors in this book draw attention to these issues as they discuss the role of failure and risk.

It is not only the general nature of schooling that makes engaging with risk and failure difficult, but as Kelly and Ellerton point out (Chap. 2), the discourses within the STEM disciplines themselves tend to emphasise knowledge as transferable "and corresponding assessment of learner retainment of this knowledge". Such traditional views of knowledge acquisition and reproduction make it difficult to operationalise creativity in STEM Education, which "requires a highly interactive, experiential culture with low risk-aversion" that can support "collaborative ideation and prototyping over time in any discipline context".

Mansfield and Gunstone (Chap. 9) delve into the ways in which knowledge is represented and developed in each of STEM disciplines, including the role of failure. They point out the serious "misalignment" between the ways in which the role of failure in each of the STEM disciplines "is represented to and perceived by those outside the discipline", and also in the ways that the individual STEM subjects are taught and learned in school. For example, the field of science is typically viewed by the general public in terms of facts and irrefutable truths, a view that is also reflected in traditional school science education through the predominance of 'recipe style' labs with pre-determined outcomes, and assessment tasks that value recall of facts. Such representations of science sit in sharp contrast with how the field of science actually progresses ("involving struggle, failure and/or serendipity") and an approach to STEM education advocated by the contributors of this book, i.e., STEM education that encourages uncertainty, doubt and risk. Interestingly, Mansfield and

Gunstone note that the concept of failure rarely appears in accounts of the development of mathematical knowledge and that school mathematics has tended to be associated with "fear of failure" (also known as "mathematics anxiety"). Thus, they advocate for including more opportunities for school students to "recognise the role and value of failure in both real-world STEM contexts and in their own learning of STEM") that may contribute to increased awareness of its meaning, value and prevalence in these fields. Their advocacy to view failure as a form of success offers both encouragement and a way forward for teachers and learners.

Several other chapters also point to the challenges for teachers in supporting student learning about failure, uncertainty and risk. While managing a risk-averse system is one significant challenge, another lies in teachers feeling sufficiently confident and prepared to teach about risk and failure to students. Kelly and Ellerton (Chap. 2) and Vincent-Lancrin (Chap. 3) link the notion of risk to teaching and learning:

> The successful teaching of creativity and critical thinking also hinges critically on teachers' attitude and in their ability to create learning environments where students feel safe to take risks in their thinking and expressions. This in turn presupposes a positive attitude towards mistakes and learner empowerment. (Kelly & Ellerton, Chap. 2)

The risk for teachers is real, but as Tan (Chap. 10) points out, if we require our STEM students to become creative and innovative, we need to support our teachers to be the same, and to be able to fully embrace the potential risk that this entails. Failure needs to be seen both as a real possibility, and as an opportunity for learning. If this is not the case, why would new ideas and approaches to be tried? The need to trust in teachers' professionalism is regularly being eroded in many educational settings through regulation and control mechanisms that limit opportunities for experimentation and risk – a feature of GERMs, as outlined earlier.

Risk-aversion in educational systems is a long-standing and pervasive challenge, even though risk and uncertainty has always been an essential part of science (see Rennie, 2020). Calls for including learning about the nature of knowledge as uncertain and as an integral part of school science education have been outlined by Fensham (2011), who detailed a Cynefin[1] framework to assist teaching complexity through certainty and uncertainty. This is but one example that teachers could adopt. STEM education can also highlight the important value and role of failure though more authentic experiences. When there is shared understanding of what failure may offer, if it is forward-focused and can be seen as an opportunity, students can gain a more authentic appreciation of the STEM disciplines.

[1] Cynefin is a Welsh word for multiple locations

11.5 Building an Alternate Interpretation of STEM Education

Based on the idea that the current 'crisis' discourse around STEM appears to narrow possibilities for learners and learning, it is my hope that this final chapter helps to bring together the messages of the book to illustrate how STEM education might be differently interpreted to broaden its possibilities and to benefit a broader range of learners. In the following section, I highlight some of the implications of STEM education for schools, teachers and learners.

11.5.1 STEM Education Opens Up Important Opportunities for Schools, Teachers and Learners

11.5.1.1 School Organisation

School organisation needs to be challenged as 'one size' does not 'fit all'. Schools need to find new and novel ways to operate that are responsive to the needs and opportunities available within their local communities. As Tan (Chap. 10) points out, "seriously integrated STEM will best come from the ways each individual school plays to its teaching and resources and environment strengths". Such new ways of working should also include empowering and trusting teachers as curriculum developers and decision-makers.

11.5.2 Empowerment of Teachers

The STEM education agenda can, and needs to be, utilised as a means to enable and empower teachers to act as agents of pedagogical change and transformation, and to enrich teachers' professional knowledge of practice. The ideas of this book may help to progress this agenda, through:

- the small, yet highly significant, role that can be played in addressing the ethical implications of the inventions that students will propose in STEM activities (see Tan, Chap. 10);
- the role teachers play in utilising local and global STEM contexts for building shared learning opportunities in creative and critical thinking (see Rennie, Chap. 7);
- the development of teacher expertise to facilitate targeted learning conversations to support students' conceptual and procedural learning outcomes (see Buntting & Jones, Chap. 5); and
- the development of new knowledge of STEM as opposed to the epistemological differences that exist across S, T, E and M (see Mansfield & Gunstone, Chap. 9).

The vision of STEM education and the kinds of school and teacher change inherent in this agenda cannot occur without significant shifts, including shifts in conceptions of what to teach, conceptions of identity as teacher, conceptions of learning and learners, and conceptions of the nature of teacher professional expertise. In turn, these shifts need to mutually reinforce shifts in approaches to curriculum design, pedagogy and assessment.

Realising a broad interpretation of STEM education will also include aspects such as:

- working to develop a shared language around the purposes and practices of STEM education;
- identifying a shared framework for STEM education, including its goals and practices, that can accommodate diverse interests and needs of learners and schools;
- recognising the crucial role of teachers as professionals, and supporting teachers to innovate, develop and trial new curriculum and practices;
- supporting teacher capacities and interest around cross-disciplinary and cross professional (i.e., those outside of schools) learning in STEM;
- identifying school leadership practices that create conditions for teacher experimentation, learning and sustainable change for STEM education; and

Consequently, there is a need to create opportunities and conditions for appropriate and sustained teacher learning that enables and promotes change. Such teacher learning in STEM education will need to examine effective approaches to STEM education, potential outcomes, and possible future directions.

11.6 Concluding Thoughts

STEM as a world-wide movement needs to attend to the nature and purposes of ‘STEM as STEM education’ that align with, and help to clarify, the purposes of schooling. As Tan (Chap. 10) points out, this would mean embracing a “humanistic vision of education, broadly based on the notion that education should strive to give to students the greatest latitude for action in the future”. This book is implicitly predicated on the premise that we must reconsider goals for schooling, and STEM in particular, but not in isolation. In this book, we have included the need to see cross-curriculum capabilities as central and fundamental goals, not as an add-on, if ‘STEM’ is to be more than a relabeling of S, T, E and M. Specifically, cross-curriculum capabilities need to be seen as central and fundamental goals of formal education. Integrated approaches to STEM education, when carefully planned and effectively implemented, can support multiple learning outcomes.

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