Amanda Berry · Cathy Buntting
Deborah Corrigan · Richard Gunstone
Alister Jones *Editors*

Education in the 21st Century

STEM, Creativity and Critical Thinking

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Preface

This is the seventh book in a series initiated by Monash University-King's College London International Centre for Study of Science and Mathematics Curriculum, in partnership with the University of Waikato. The Monash-King's College Centre was established in 2002 with initial support from the Monash University Research Fund (New Areas). The Centre for Science, Mathematics and Technology Education at Monash University and Waikato University's Technology, Environmental, Mathematics and Science (TEMS) Education Research Centre have had a formal partnership agreement since 2003 and have worked cooperatively in many areas.

The first book in the series, *The Re-emergence of Values in Science Education* (D. Corrigan, J. Dillon and R. Gunstone [Eds.], 2007, Rotterdam: Sense), considered the state of science education in the twenty-first century through the lens of values. The book presented a 'big picture' of what science education might be like if values once again became central in science education. At the time, the overwhelming experiences of those who were teaching science were in an environment that had seen the de-emphasis of values fundamentally inherent in both science and science education. There was a disparity between the evolutionary process that science was – and still is – undertaking and that undertaken by science education (and school science education in particular).

In the second book, *The Professional Knowledge Base of Science Teaching* (D. Corrigan, J. Dillon and R. Gunstone [Eds.], 2011, Dordrecht: Springer), our intent was to explore what expert science education knowledge and practices may look like in the then slowly emerging 'bigger picture' of the re-emergence of values, which we saw as a logical step from the first book's exploration of values. We noted in the Foreword to this book that the focus of the book was on 'exploring what expert science education knowledge and practices may look like in the emerging 'bigger picture' of the re-emergence of values'.

In the third book, *Valuing Assessment in Science Education: Pedagogy, Curriculum, Policy* (D. Corrigan, R. Gunstone and A. Jones [Eds.], 2013, Dordrecht: Springer), we took what we considered to be another logical next step in the sequence of foci begun with our exploration of values: assessment. The reality of education is that it is assessment that is almost always the strongest force shaping teacher development and behaviour, the implemented curriculum, student approaches to learning, etc. Consequently, the third book considered the 'big picture' of assessment in science education, from the strategic and policy level to that of classrooms. However, while some classroom case studies were presented, they focused more on teachers than students, and so considered assessment more in terms of what teachers plan and do rather than the impacts of assessment on students.

The fourth book, *The Future in Learning Science: What's in It for the Learner?* (D. Corrigan, C. Buntting, J. Dillon, A. Jones and R. Gunstone [Eds.], 2015, Dordrecht: Springer), considered the learning of science in contemporary education: the forms of science that represent the nature of science in the twenty-first century, the purposes we might adopt for the learning of school science, the forms this learning might better take and how this learning happens. Of particular concern was the need to better engage students with their school science and the need to place the burgeoning range of digital technologies into a more informed context than the narrow and uncritical contexts in which they are too commonly being positioned. Additionally, we sought to represent and value the perspective of the learner as an important overarching theme.

The fifth book, *Navigating the Changing Landscape of Formal and Informal Science Learning Opportunities* (D. Corrigan, C. Buntting, A. Jones and J. Loughran [Eds.], 2018, Cham: Springer), championed research involving learning opportunities that are afforded to learners of science when the focus is on linking the formal and informal science education sectors. We use the metaphor of a 'landscape' to emphasise the range of possible movements within a landscape that is inclusive of formal, informal and free-choice science education opportunities, rather than the not uncommon formal sector assumption that the informal sector should somehow serve the formal, and that free choice is not part of education at all. In addition, the book explored opportunities for informing formal school science education via the perspectives and achievements of the informal and free-choice science education sectors.

Then the sixth book, *Values in Science Education: The Shifting Sands* (D. Corrigan, C. Buntting, A. Fitzgerald & A. Jones [Eds.], 2020, Cham: Springer) returned to an explicit focus on values, more than a decade after the first book in this series. In that first book, it was evident that different cultures have different traditions in relation to the place of values in their school science curriculum and that these traditions were being challenged. In this sixth volume, authors reflected on how values are centrally associated with science and its teaching, as well as the wide range of factors that influence science education. These include sociocultural, philosophical and psychological influences; curriculum; the nature of science; formal and informal education settings; the relationship between science, technology, society and the environment; teaching and learning practices; assessment and evaluation; teacher education; and classroom climates. As suggested by the second half of its title, the book sought to capture the persistent but vulnerable nature of values in the face of forceful influences on the education landscape.

In this seventh book, we focus on two major and increasingly global trends that impact directly on curriculum in the sciences and mathematics, engineering and technology. The first of these trends is, unsurprisingly, 'STEM'. This acronym for Science, Technology, Engineering, Mathematics, is today used continuously by, it seems, all groups with concerns for formal education – from classroom teachers to national politicians. It is easy to forget that this ubiquitous use of STEM did not even seriously begin until the present century. It can also be easy to overlook that STEM is used for more than one purpose. Our concern in this volume is with issues relevant to STEM Education. The second trend is for school curriculum in particular to embrace cross-curriculum goals ('competencies' or 'capabilities'), usually intended to be woven into traditional single-discipline subjects. Two of these competences have often been seen as specific parts of science or mathematics curricula – 'creativity' and 'critical thinking'. These two, with STEM Education, are themes through the chapters of this book as these issues are addressed in a wide range of contexts, from individual classrooms to reconceptualising the purposes of STEM Education.

We used the same approach to the creation of this seventh book as we did with the previous six. In seeking to achieve a cohesive contribution to the literature while enabling the authors to assert their own voices without restrictive briefs from us as editors, we again hosted a 3-day workshop involving all the authors to facilitate a more interactive and formative writing process. A first draft of all chapters was distributed prior to the workshop, enabling intensive discussions of individual chapters and feedback to authors and considerations of the overall structure and cohesion of the volume. Authors then rewrote their contributions in the light of the group's feedback. As with the previous books, the workshop was scheduled around the European Science Education Research Association (ESERA) conference in Bologna and took place at the Monash University Centre in Prato (Italy).

This writing process had previously been used very successfully in the production of two other books in which the editors had variously been involved: P. Fensham, R. Gunstone & R. White (Eds.), 1994, *The Content of Science: A Constructivist Approach to Its Teaching and Learning*, and R. Millar, J. Leach & J. Osborne (Eds.), 2000, *Improving Science Education: The Contribution of Research*. More recently, the approach has been adopted by other science education researchers. We believe, strongly, that this process significantly improves the quality of the final product and provides an opportunity for what is sadly a very rare form of professional development for academic researchers – formative, highly collaborative (and totally open) discussions of one's work by one's peers.

We gratefully acknowledge the funding of the workshop through contributions from Monash University and Waikato University and the commitment, openness and sharing of all participants in the workshop.

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Peter Ellerton is Curriculum Director of the University of Queensland's Critical Thinking Project and Senior Lecturer in the School of Historical and Philosophical Inquiry. He has a master's degree in science and a PhD in philosophy, and taught in high schools for many years. Peter's areas of research interest include public reasoning, science communication, argumentation and critical thinking in education. His passion is working with educators to enable a teaching for thinking focus across all year levels and subject areas.

Richard Gunstone is Emeritus Professor of Science and Technology Education at Monash University. His published research has involved the areas of learning, teaching and teacher development, curriculum and assessment, at all levels of education; his past work includes editorship of the Encyclopedia of Science Education (Springer, 2015). His current interests include the changing natures of the disciplines of science and of technology in the twenty-first century, and the implications of these changes for school STEM in general and the sciences in particular. In 2014, he received the Distinguished Contributions to Research Award from the National Association for Research in Science Teaching.

Alister Jones is Research Professor and Senior Deputy Vice Chancellor at the University of Waikato, New Zealand. He had a leading role in developing New Zealand's technology education curriculum; has been consulted on educational development in Australia, the UK, USA, Hong Kong, China, Chile and Thailand; and is the director of a number of educational companies. He is a founding board member of the Forum for World Education.

Robert Kelly is Associate Professor in the Faculty of Arts at the University of Calgary, Canada, and Academic Coordinator of the Collaborative Creativity for Social Innovation and Human-Centred Design graduate program at the University's Werklund School of Education. He has pioneered research in the areas of collaborative creativity, creative development, and design thinking for innovation in teacher education through course and program design at his home institution and as an invited visiting scholar at numerous postsecondary institutions in Canada.

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Paula Mildenhall is Associate Professor and the Associate Dean of Teaching and Learning in the School of Education at Edith Cowan University in Perth, Western Australia. Over the past 25 years, Paula has held teaching and leadership roles across the education sector in primary and tertiary settings, both in Australia and internationally. Her research focuses on mathematics and STEM education in primary schools and also on how pre-service teachers may effectively learn in tertiary settings.

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Kathy Smith is Senior Lecturer in the Faculty of Education at Monash University, Australia, with specialisations in primary science education and teacher professional learning. She is also the Course Leader for the Graduate Certificate in STEM Education at Monash University. Kathy began her career as a primary classroom teacher and has been involved in science education in a range of roles for the last 30 years. Her research interests include understanding more about the conditions that promote quality teacher professional learning, primary science education, STEM education, and the relationship between teacher thinking and pedagogy.

Michael Tan is Lecturer (Research Scientists) at the National Institute of Education, Nanyang Technological University, Singapore. His research interests are in curriculum studies and teacher development, with a specific focus on science education. In recent years, he has been studying the implementation of STEM in makerspaces, with an intention towards nurturing students' critical perspective, creativity and wisdom.

Stéphan Vincent-Lancrin is Senior Analyst and Deputy Head of Division at the Organisation for Economic Co-operation and Development (OECD), Directorate for Education and Skills. He leads work on innovation in education and education for innovation. He works on digitalisation in education and has edited the OECD's *Digital Education Outlook 2021: Pushing the Frontiers with AI, Blockchain and Robots*. He is also interested in non-technological innovation, for example, how teachers can foster and assess students' creativity and critical thinking, and more broadly, in the determinants of innovation-friendly ecosystems education.

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Chapter 1
STEM Education Matters

Cathy Buntting, Richard Gunstone, Amanda Berry, Deborah Corrigan, and Alister Jones

1.1 The Pandemic of 2020

Writing this chapter in the latter part of 2020, we are mindful of the many ways that the world has been dramatically defined and transformed by the impacts of COVID-19. The global pandemic has shone the spotlight on a plethora of human concerns that, while not new, have been highlighted in new ways: our interconnectedness and vulnerabilities as a species, our propensity for both compassion and selfishness, the inequities that stretch across and within borders, and ultimately our resilience. Across the world stage, we've seen multiple scenarios playing out – the majority unscripted and continuing to evolve as new developments emerge. Evidence from across the STEM disciplines – science, technology, engineering and mathematics – has shaped individual, community and national responses, but in different ways. While some jurisdictions committed to strategies of reduction and elimination, others pinned hopes on 'herd immunity' and the development of vaccines, and in some places politics superseded acceptance of the spectrum of evidence from the fields of STEM about COVID-19 and how best to respond. In many instances, poverty that preceded the pandemic tragically eliminated choice. In other instances, wilful ignorance had deathly consequences.

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Within these world-wide times of change, the central themes of this book – contemporary education, STEM, criticality and creativity – are even more powerfully relevant. While 'science' may be leading the way in terms of seeking to understand the novel SARS-CoV-2 virus and its variants, epidemiological modelling is based on integrating mathematical, computing and scientific data, processes and interpretations. Innovations – from COVID testing and vaccine development and its mass production and distribution, to digital mechanisms that support contact tracing and the setting up of isolation protocols and facilities – all rely on systems-approaches that integrate all the STEM epistemologies, including critical and creative approaches to knowledge development and deployment. STEM, criticality and creativity remain key to the recovery and rebuilding that societies and economies will urgently need moving forward.

As educators and education researchers, we've been heartened by the incredible innovation and commitment shown by countless teachers across formal and informal education contexts and across all ages of learners. However, inequities have also been exacerbated – some children and families are more exposed to the negative economic and social impacts of regional and national 'lockdowns'. In some contexts children are no longer accessing education at all because they have been pushed prematurely into employment; those children who do not have the digital resources necessary to access 'learning from home' initiatives in contexts where schools have been closed have in many places essentially been excluded from schooling; and school districts and jurisdictions that do not have the resources to support teachers to effectively deliver online learning opportunities have been disproportionately impacted.

How does education research speak with relevance into a climate such as this one? While there was no thought of anything like COVID-19 when we first began working on this book project in 2018, global issues such as sustainable economic development, climate change and disease management were at the forefront of many STEM education initiatives. There has been long-standing recognition in many countries that traditional school structures need to be better preparing young people as citizens of and contributors to a knowledge economy and a twenty-first century society. Our hope in bringing this particular group of academics together to write, discuss, and rewrite was that we would be able to identify key themes that could help to progress the development of STEM education internationally.

1.2 The Power of the 'STEM' Acronym

The rapid popularisation of STEM – science, technology, engineering and mathematics – came after its use in 2001 by staff at the United States National Science Foundation (NSF) (e.g., Hallinen, 2015), primarily when NSF staff were testifying to Congressional committees in Washington. NSF had

> previously used the acronym SMET when referring to the *career fields in those disciplines or a curriculum that integrated knowledge and skills from those fields*. In 2001, however, American biologist Judith Ramaley, then assistant director of education and human resources at NSF, rearranged the words to form the STEM acronym. (Hallinen, 2015; emphasis added)

However, 'STEM' had been used as an acronym at least as early as the 1990s, and often in the context of 'STEM education', including in a 1998 five-year, multi-million dollar grant funded by the NSF, titled "The Science, Technology, Engineering, and Mathematics Teacher Education Collaborative (STEMTEC)" and managed by the already established "STEM Education Institute" at the University of Massachusetts, Amherst – an Institute that continues today.

Over the last two decades the two broad meanings explicitly associated with STEM by the NSF in 2001 (career fields and integrated curriculum) have both been pursued, even though the two are quite disparate. Additionally, they are at times joined by a third meaning, a collective noun for the separate disciplines of the sciences, mathematics, engineering and technology. Quite why STEM has been so pervasive in political rhetoric, public discussion, and education policy when earlier movements such as 'science and technology' clearly were much less influential is likely a consequence of both the short, word-form of the label and the context in which it emerged (a context in which, for example, technologies were very rapidly becoming even more central to daily life while at the same time, and just as rapidly, becoming more and more complex). Whatever the reasons, STEM education has captured global interest and become an educational phenomenon.

Although STEM education is often cited in political and policy domains as being important, even critical, for economic growth, we do not see this as a significant – or helpful – driver for school STEM education. Rather, we see the power of school STEM education in relation to the future of learners more in terms of their "belongingness in society" than in attempting to forecast specific STEM employment possibilities. In general terms, there is an obvious disconnect between arguments that school STEM education should focus on specific preparation for future employment and the common observation that a large proportion of future jobs cannot yet even be imagined. Further, critics of school STEM education for solely economic/employment reasons point to the vast array of data showing there is an ongoing, substantial and still little-changing lack of diversity in STEM career paths and STEM-related employment across gender, ethnicities, cultures and socio-racial groups (e.g., Allen-Ramdial & Campbell, 2014; Estrada-Hollenbeck et al., 2011; Leigh et al., 2020; Pew Research Centre, 2018; UNESCO, 2017).

Our collective view that it is the integrated curriculum meaning of STEM on which school education should focus, and not the career/employment view, is reflected in the chapters of this book. Specifically, we position such integrated STEM education as working to remove barriers between the four disciplinary areas of science, technology, engineering and mathematics, while retaining the value of disciplinary knowledge and skills. Our premise is that everyone needs to be STEM-literate if our communities are to effectively respond to multi-faceted economic, social and environmental challenges such as those foregrounded by COVID-19 and climate change (Corrigan, 2020).

1.3 Cross-Curriculum Capabilities: A Major Curriculum Trend in the 21st Century

As we began our conversations in 2018 about important possibilities for a book to explore contemporary issues with STEM education, we were conscious of global changes in broader curriculum thinking and planning. This included a major shift towards curricula advocating for cross-curriculum ‘competencies’ or ‘general capabilities’, with these often generically grouped together as ‘21st Century skills’. These capabilities are relevant to all subject domains of a curriculum, and are argued to be too significant to the development of learners to be ignored. Such cross-curriculum competencies are now required in many systemic curriculum prescriptions, and are central themes in a number of multi-country projects promoting curriculum thinking (e.g., the ‘competencies learners need to succeed’ in Fadel, Bialik & Trilling, 2015 and the OECD’s *Future of Education and Skills 2030*, n.d.). Among the competencies variously identified in these curricula are two that have long been associated with education in the separate disciplines of STEM – critical thinking and creativity. Current movements in STEM education and broader cross-curriculum competencies both reinvigorate and reinforce the deep importance of creativity and critical thinking in the separate disciplines of STEM and in integrated STEM education. As a consequence, in our invitations to contributing authors for the writing workshop and this subsequent book we specifically identified these two competencies as being of particular interest. (An outline of the invitation and the nature and purpose of the workshop is given in the Preface to this book.)

1.4 The Chapters of this Book

As we note at the beginning of this chapter, the onset of the COVID-19 pandemic came well after the planning of this book and the writing of draft chapters. Nevertheless, and completely unexpectedly, this pandemic provides dramatic global and life-determining examples of science, of mathematics, and of technological advancement. Both creativity and critical thinking have been made clearly evident as central to medicine, social policy, and the reporting of science, mathematics, engineering and technology in mass and social media. When presented with situations where accepted norms are no longer appropriate, available or encouraged, as in the pandemic self-isolation scenarios experienced across the globe, the need for new ways to live and learn becomes fundamentally important. One important lesson from the COVID-19 pandemic has been the demonstration of the profound importance of collaboration (not competition) between professionals of different disciplines – including the STEM disciplines.

Throughout the chapters of this book there is specific concern with the roles of creativity and critical thinking in contemporary and future STEM education. Therefore, Chap. 2 focuses directly on creativity and critical thinking – what these are, and what characteristics they have. One of the authors, Robert Kelly, has a substantial history in researching creativity and teaching about the nature and development of creativity; the other, Peter Ellerton, has the same in critical thinking. The two have co-authored a single chapter because, as they write,

> [t]he application of the concepts of creativity and critical thinking into educational practice across the STEM disciplines [...] requires an integrative approach as these two concepts are so heavily interrelated in practice on so many levels; they are mutually dependent concepts.

In the first substantive section of Chap. 2 Robert Kelly defines creativity in terms of having characteristics of a sequence of thought, a sequence of actions, and a novel adaptive production that occurs within a social context. But, he notes, definition is not enough. It is important for educators, in STEM or otherwise, to not only engage in creativity but to also educate others in creative practice – that is, to be involved in the operationalisation of creativity. His proposed mode of creative development with which educators need to engage includes consideration of the development of collaborative and communication capacity as groups come together to engage in the creative process. This includes ideation and prototyping in the production of a novel and useful solution or artefact. Engaging in the creative process also requires some degree of self-initiated development fuelled by intrinsic motivation, a growing appreciation for the complexity of the disciplines within which one operates, and a strong sense of the discipline expertise one has to contribute to the process.

Peter Ellerton then continues Chap. 2 by addressing the nature and characteristics of critical thinking. He notes that while critical thinking does not have a specific and unique disciplinary home, it has a logical academic home in philosophy because philosophy "provides a rigorous normative framework for understanding critical thinking". Critical thinking is widely accepted to involve skills (e.g., argument construction, evaluation, communication), inquiry values (e.g., values associated with the process of inquiry such as accuracy, reproducibility, coherence), and inquiry virtues (characteristics of an individual critical thinker rather than a process of critical thinking, e.g., open-mindedness, tolerance, honesty, charity). Kelly and Ellerton argue that creativity and critical thinking, in their mutual dependence, are both developed under conditions that include doubt, collaborative investigation, and shared commitment to completion of the task or goal that initiated the development. None of the entities at the heart of this book – STEM education, creativity and critical thinking – exist in isolation. They are entwined. Understanding how they are entwined and in what contexts, and how creativity and critical thinking are central to STEM education, is a consistent focus throughout the subsequent chapters of the book.

In Chap. 3, Stéphan Vincent-Lancrin considers what the capabilities of creativity and critical thinking might specifically involve when exemplified in school science education, and how one might consider the development of each of these among students. He describes a multi-country OECD project to develop both domain-general and science domain-specific conceptual rubrics for creativity and for critical thinking, and lays out the products of the project. He then illustrates the science-specific rubric via application in two different science curriculum units, and outlines teaching and learning strategies aligned to both the development of creativity and critical thinking, and to the rubrics. One of the powerful outcomes from using both domain-general and domain-specific conceptual rubrics is in them providing a shared language in which to talk about creativity and critical thinking. Vincent-Lancrin next uses science as an example of how such concepts can be developed within a specific discipline with this shared language. Readers are invited to extrapolate from these insights to consider the implications for such conceptual development not only in the discrete disciplines within STEM but also within integrated STEM education approaches in their own contexts.

While creativity and critical thinking continue to be emphasised in Chap. 4, Bronwen Cowie and Paula Mildenhall take as central themes notions of social justice, equity, and the important role of empathy in engaging learners in authentic STEM contexts, including genuine considerations of possible action. Using three examples, Cowie and Mildenhall convincingly demonstrate that it is necessary to walk in the shoes of others if students are to give authentic, respectful consideration to taking some agency over potential subsequent actions in response to a real STEM issue. Specifically, the three different vignettes from STEM primary school classrooms demonstrate the differing paths empathetic actions can take for the learner. They also demonstrate that while knowledge is necessary, it is not sufficient for students to be willing and able to take constructive action. It is the development and exercising of empathy, alongside critical and creative thinking, that assists such action.

The use of case studies of primary school classrooms to illustrate significant issues in STEM education and creativity and critical thinking continues in Chapters 5 and 6. First, Cathy Buntting and Alister Jones take us into a senior primary school STEM classroom in which an experienced, committed and clearly expert STEM teacher has his class building simple hydraulic machines. In this detailed case study, Buntting and Jones demonstrate the nature of student learning in this specific integrated STEM context, and, particularly, the importance of focussed conversations between teacher and students in supporting the development of the students' creative and critical thinking. The chapter is a powerful illustration of the ways in which the multiple knowledges held and used by expert teachers have major impact on the development of quality student learning in their classrooms.

In Chap. 6, Deborah Corrigan, Debra Panizzon and Kathy Smith provide two case studies of individual teacher development concerned with implementing STEM teaching with a focus on creativity and critical thinking. Corrigan, Panizzon and Smith begin by providing the background to their own thinking about STEM, creativity and critical thinking before laying out the two examples of teachers who, after experiencing a relevant extended professional learning programme, consider the implementation in their classroom of STEM with a focus on developing creativity and critical thinking. The chapter identifies some of the decisions that influenced the strategies, practices and approaches used by the participating teachers in this implementation.